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THE UNIVERSITY OF ALBERTA

NATURE AND GENESIS OF THE AFTON COPPER DEPOSIT, KAMLOOPS, BRITISH COLUMBIA

by

(C) HARLEY H. K. HOILES

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY

EDMONTON, ALBERTA

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THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "Nature and Genesis of the Afton Copper Deposit, Kamloops, British Columbia", submitted by Harley H. K. Hoiles, in partial fulfilment of the degree of Master of Science.

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Date . . April 3. 1978

ABSTRACT

The alkaline suite of Cherry Creek hypabyssal porphyries intruded a coeval proximal volcanic succession during the Upper Triassic metallogenic-orogenic event in south-central British Columbia. Attendant hypogene and subsequent supergene metallization of the Cherry Creek porphyries resulted in a commercial grade orebody consisting of 30.84×10^6 tonnes of 1.0% copper, 0.58 ppm gold and 4.19 ppm silver.

Strong structural control on both a regional and local scale is evident for the emplacement of the host Cherry Creek intrusive phases, distribution of hypogene metalliferous minerals and supergene evolution of the deposit. Prexisting structures, renewed shearing and fracturing, in part related to Eocene uplift and block faulting, coupled with the enhanced permeability and porosity as a result of hydrothermal alteration are thought to be major supergene controls.

The orebody is classified as a stockwork type, as the ore minerals occur principally in disseminations and veinlets. Zonation in regards to the mode of occurrence, nature of the metalliferous minerals and alteration types is present. A deeper hypogene zone consists of bornite-chalcopyrite $\pm$ pyrite mineralization with lesser amounts of sulfosalts and minor chalcocite. Native copper-chalcocite, copper oxides and copper carbonates, and hematitic limonite define the supergene-oxidation blanket zone. A peripheral pyritic halo, up to 700 m wide, encloses the main orebody, which is transected by a zone of intense magnetite veining at its eastern margin.

Eight sequential and overlapping stages of metallization/alteration

and veining are recognized. Potassic, propylitic, and phyllic alteration types are present, with a poorly defined zonation consisting of a deeper central potassic zone grading outward to propylitic and phyllic types. A considerable amount of telescoping of the hypogene ore/alteration assemblages is evident, with the bulk of the ore-grade material coincident with propylitic followed by potassic alteration.

The copper-bearing sulfides all approach their idealized stoichiometric formulae. Gold and silver were confirmed in both hypogene and supergene zones with trace amounts of molybdenum detected in the hypogene ore zone. Arsenic and selenium are present in the ore either as sulfosalts or admixed in the sulfide phases. Samll deviations from stoichiometry in bornite and chalcopyrite are related to the presence of arsenic and selenium.

Sulfur isotope analyses illustrate that the S^{34} values of the Afton deposit are comparable to other deposits of magmatic hydrothermal origin, in displaying a mean S^{34} value close to zero per mil and a small standard deviation. Enrichment of the lighter isotope, S^{32}, was in the order Py Cp Bn, and this, together with the textural evidence suggests an approach toward equilibrium for the formation of the main part of the hypogene orebody. Chalcocite from the supergene zone was enriched in S^{34} relative to the hypogene sulfides, indicating that where other evidence is lacking, sulfur isotopes may be used to distinguish supergene from hypogene sulfides.

On the basis of sulfur isotope geothermometry, temperatures of hypogene ore deposition ranged from 172° C to 388° C and decreased from centre to periphery. An average temperature of 360° C was obtained for the main hypogene chalcopyrite-bornite ore zone. Moderate to extreme depletion in S^{34}

in peripheral and paragenetically later pyrite-chalcopyrite assemblages is attributed to a temperature decrease, disequilibrium conditions, changes in pH and f_{O_2}, or combinations thereof.

ACKNOWLEDGEMENTS

The writer wishes to express his sincere gratitude to Dr. R.E. Folinsbee for suggesting this research topic and for his continuous support throughout the project. Dr. R.D. Morton also provided many helpful suggestions during the course of study, and his assistance is gratefully acknowledged.

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Chapter 1

INTRODUCTION

A. OBJECTIVES AND OUTLINE OF STUDY

The author's curiosity about the Afton copper deposit originated while he was employed at the nearby Lornex mine during the summer of 1972. At that time, the abundance of native copper and chalcocite, revealed during the initial drilling of the Afton orebody, was recognized as being atypical of known deposits in the area. With the incentive that the unique ore mineralogy of the deposit might be indicative of a preserved 'Arizona type' supergene zone, the writer was prompted to undertake this study in the fall of 1972.

The purpose of this study will be to present various geological and geochemical factors that are thought to have influenced formation of the Afton orebody, and hence provide a basic understanding of ore deposition. The main objectives of the study were:

(1) to present a comprehensive review of the regional geological setting in order to establish those parameters which may have affected regional control of ore deposition;

(2) to establish the local and immediate geological environment that existed at the time of hypogene and supergene events;

(3) to present, through isotopic and geochemical studies, certain physio-chemical conditions that influenced ore formation;

(4) to propose a model and history of ore deposition.

The data for this study was obtained by field and experimental work. Field work consisted of examining outcrop in the Afton area together with

logging and sampling diamond drill core. Laboratory research was conducted by means of optical, electron microprobe, mass spectrometer and atomic absorption techniques.

The subject matter is presented in eight chapters. Aspects of the regional and local geology will be discussed in Chapters II and III respectively. The detailed geology of the deposit, including information on host rock lithology, orebody geometry, and structure is presented in Chapter IV. The distribution of the ore minerals and ore textures is discussed in Chapter V. Gangue minerals, wallrock alteration assemblages, and paragenesis are considered in Chapter VI. Ore geochemistry and stable isotope data of sulfur are presented in Chapter VII together with interpretations on source of ore fluid and temperature of ore deposition. In Chapter VIII, the writer proposes a model of ore formation. The remainder of the introductory chapter deals with location, access, physiography, and history of the Afton deposit.

B. LOCATION, ACCESS, PHYSIOGRAPHY

The Afton copper deposit is located at latitude $50^{\circ}39.5'$ North by longitude $120^{\circ}31'$ West, some 13km west of the town of Kamloops, British Columbia (Fig. I - 1). The orebody is readily accessible, as it is situated some 800m south of the rerouted Trans-Canada Highway, in an area of rolling sagebrush and grassland (Afton Mines Ltd., Annual Report, 1977, in pocket).

Physiographically, the Afton area occupies a part of the Thompson Plateau, a continental area that has been subject to erosion since the Early Cretaceous. The Thompson Plateau is a subdivision of the larger

Interior Plateau, which forms part of the physiographic Interior System of the Cordillera. The Interior System in British Columbia, as distinguished from the mountainous terrain to the east and west, is essentially an elevated platform consisting of upland blocks divided by reticulate systems of major valleys. As a result of this juxtaposition, a dry steppe climate persists in the Kamloops area with an annual precipitation of 3.88 cm. Several ephemeral alkali ponds dot the countryside, one of which overlies the Afton orebody.

The Afton deposit, situated at 640 m elevation, occupies part of a midland (Fulton, 1975). The midland forms a broad basin-like feature which slopes gently northward to the Thompson River valley. This midland is believed to be a pre-Eocene inherited feature (Uglow, 1923).

Unconsolidated sediments in the area of the deposit consist largely of till, with minor sand, silt and gravel. Average thickness of overburden is in the order of 19.33 m. Bedrock exposure in the vicinity of the Afton deposit is poor (< 10%), hence detailed geological interpretation is based largely upon diamond-drill core data.

C. HISTORY

References to copper mineralization in the Kamloops area date back to the year 1871 (B.C. Minister of Mines, 1871), with the first reference to the Afton Mines area being found in reports for the year 1898. At that time, bornite and chalcocite were reported from a 110 m deep shaft referred to as Pothook, and chalcopyrite and malachite were revealed in an open cut some 33 m northeast of the shaft (B.C. Minister of Mines, 1898). Situated 1167 m southeast of the presently known Afton orebody, the Pothook shaft

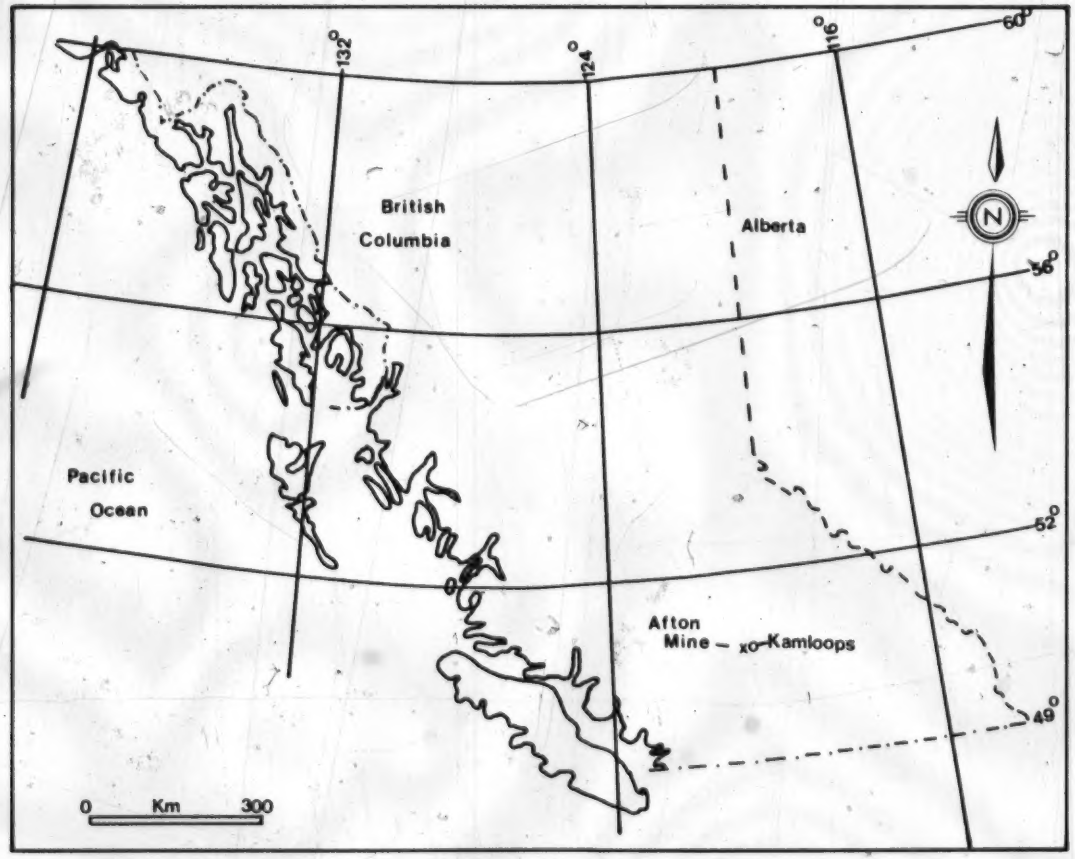


Fig. I - 1. Location map of the Afton copper deposit, British Columbia.

and surrounding area remained the focus of exploration activity for many years. In 1949 a prospector named Axel Berglund staked eight claims over the Pothook workings and named the group 'Afton', which means 'evening' in Swedish (Millar, 1973). From 1949 to 1960 several companies optioned the Afton claims and conducted exploration on the group and adjacent ground. The companies involved were : Kennecott Copper Corporation in 1952; Graham Bousquet Gold Mines Limited in 1956 - 57; Noranda Mines Limited in 1958; and New Jersey Zinc Exploration Company Limited in 1960. Their efforts, which were concentrated in the vicinity of the Pothook shaft, failed to delineate an orebody.

In 1964, while working as a drilling contractor on a nearby property, C.F. Millar became interested in the Afton ground. He persuaded Colonial Mines Limited to conduct percussion drilling near the Pothook shaft, but the program was shortlived, and terminated after eleven holes. The following year, Mr. Millar formed his own syndicate, Afton Mines Limited, and continued work in the area. At that time, new claims, which were later to be the site of the Afton discovery, were staked adjacent to the Trans-Canada Highway. Mr. Millar's company also carried on with percussion drilling and conducted an extensive induced polarization survey.

In 1967, with the view to obtain public financing, a private consultant's report recommended diamond drilling nine widely spaced holes centered on induced polarization 'highs'. In 1969 a public underwriting was completed, and during 1970 five of the nine holes were drilled. Mr. Millar then suspended the remainder of the drilling. Results showed that an induced polarization 'high', located south of the Pothook shaft, was caused by disseminated pyrite. Another hole, situated 1167 m northwest of

the shaft, was drilled on a minor 'bulge' in a main induced polarization anomaly. The hole penetrated the east half of the presently known Afton orebody, intersecting 83.33 m of 0.41% copper in a zone of abundant magnetite veining. In August, 1971, after agreements with Duval Corporation and Quintana Minerals had expired, the property reverted back to Afton Mines Limited.

In September, 1971, Mr. Millar's syndicate still had $70,000.00 left in the treasury. The Directors decided to commence with a new percussion drilling program in the area where the aforementioned copper-magnetite zone was encountered. Most of the seventeen holes returned significant intersections of mineralization in the form of native copper and copper sulfides. Further reserves were indicated, as several of the holes bottomed in ore grade material. Drilling was suspended for a short period to arrange financing and was resumed, with the addition of diamond and rotary rigs, in November, 1971.

Canex Placer Limited entered the Afton financial picture on March 22, 1972. Through their wholly owned subsidiary, Canadian Exploration Limited, Canex purchased from Afton Mines Limited 100,000 treasury shares for a cash consideration of $350,000.00. Canex was also to provide advisory services in connection with the exploration and development of the Afton property and were in return granted the right of first refusal to participate in future financing. By a second agreement, dated May 30, 1972, Canex was granted exclusive possession, management and control of the property. In addition, the agreement provided that Canex proceed with exploration and development at its own expense with a view to placing the property into production (Afton Mines Ltd., 1972).

By early June, 1972, Teck Corporation and Iso Mines Limited had jointly purchased, on the open market, in excess of 50% of the issued capitol of Afton Mines Limited. Control of the property was immediately contested by Teck Corporation which commenced legal action to set aside the May 30, 1972 agreement. Due to the litigation, work was suspended on the property for a period of six months. On December 8, 1972, the Supreme Court of British Columbia dismissed the action brought upon by Teck Corporation. Drilling was then resumed in early 1973 under the management of Canex. Teck Corporation, however, appealed the court ruling and won. Following the verdict, the remainder of the feasibility study was managed and financed jointly by Teck Corporation and Iso Mines.

The production decision was announced by Teck Corporation in November, 1975. According to the latest reports (Afton Mines Ltd., Annual Report, 1977, in pocket), production has commenced at a rated recovery and plant capacity of 87% and 7,000 tons per day, respectively.

Chapter II

REGIONAL SETTING

A. INTRODUCTION

Regional geological mapping of the Afton area has been carried out by officers of the Geological Survey of Canada on a scale of one inch to four miles. The Nicola map-area, in which the Afton deposit is situated, was mapped by Cockfield in 1948. The adjoining areas, which include the Princeton, Ashcroft, Vernon and Bonaparte Lake map-sheets, have been mapped respectively by Rice (1947), Duffell and McTaggart (1952), Jones (1959), and Campbell and Tipper (1971).

The regional geology is shown on Figure II - 1. The map-area straddles portions of three major tectonic elements of the Canadian Cordillera: the Quesnel Trough; Omineca Geanticline; and Pinchi Geanticline (Fig. II - 2a). The Quesnel Trough (Roddick et al., 1967), which is a partly fault-bounded depositional feature, is underlain by Lower Mesozoic and younger rocks. The Quesnel Trough is flanked by the Omineca and Pinchi Geanticlines, and within the map-area (Fig. II - 1) the margins of the geanticlines are composed mainly of Paleozoic Cache Creek Group rocks. The regional stratigraphic sequence is presented in Table II - 1.

B. REGIONAL GEOLOGY

1. Cache Creek Group

The oldest rocks exposed in the map-area (Fig. II - 1) belong to the Cache Creek Group, so named by Selwyn (1872) from its type locality near the settlement of Ashcroft. Since the pioneering work on the group, several

Figure II - 1, Legend

LATER TERTIARY VOLCANICS

Plateau and valley basalts

EARLIER TERTIARY VOLCANICS

Princeton and Kamloops groups

UPPER CRETACEOUS TO MID-TERTIARY SEDIMENTS

Pasayten, Princeton, Kamloops groups and Coldwater formation

JURASSIC AND LOWER CRETACEOUS

Ashcroft, Dewdney Creek, Jackson Mountain groups (sediments)
Spences Bridge, Kingsvale groups (mainly volcanics)

UPPER TRIASSIC

Nicola group(sediments and volcanics)

PENNSYLVANIAN AND/OR PERMIAN

Cache Creek group

PLUTONIC ROCKS

Later (Jurassic and later)

Earlier (Jurassic and Upper Triassic)

Serpentine

Synclinal Axis

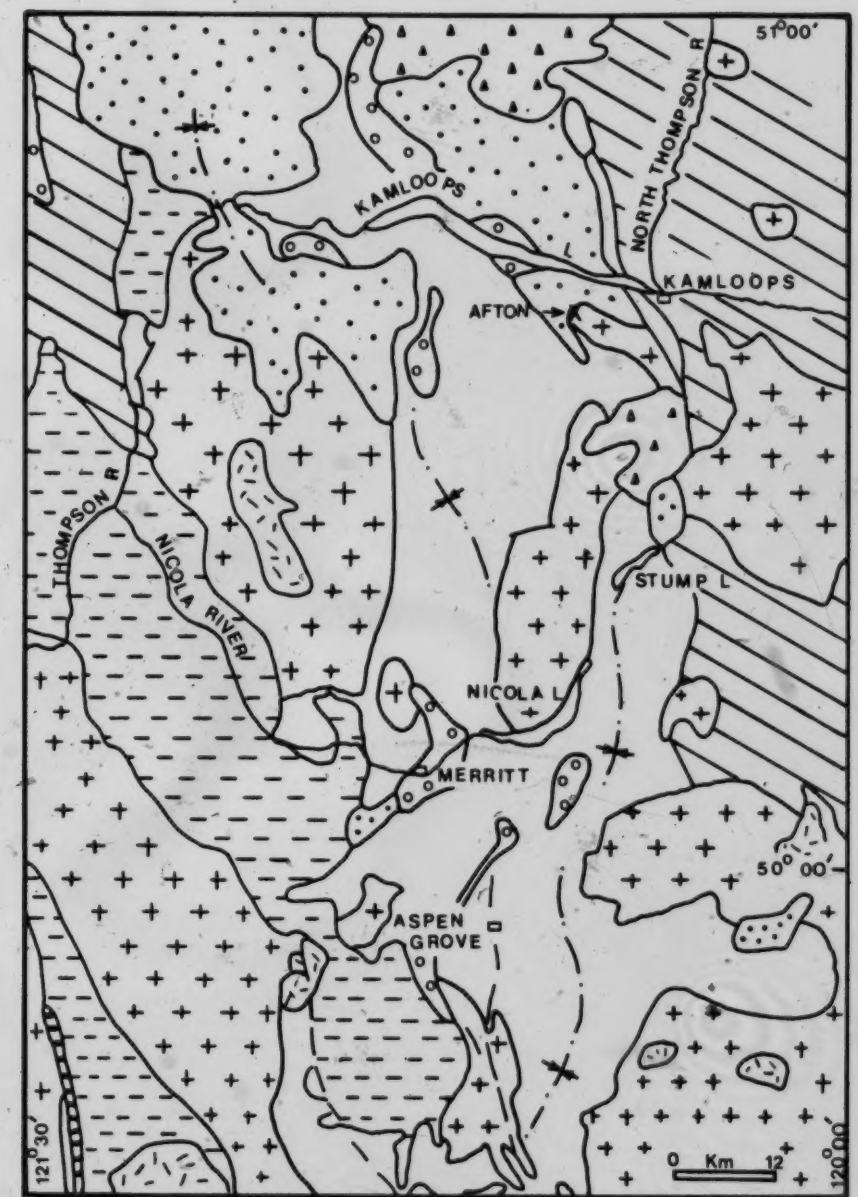


Fig. II - 1. Regional geologic map of south-central British Columbia.

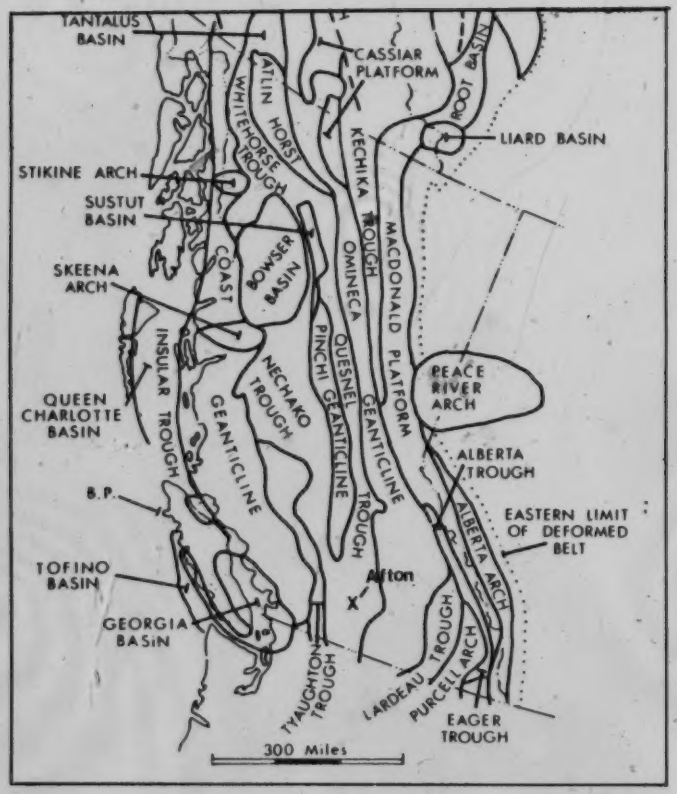


Fig. II - 2a. Tectonic elements of the Canadian Cordillera, British Columbia.

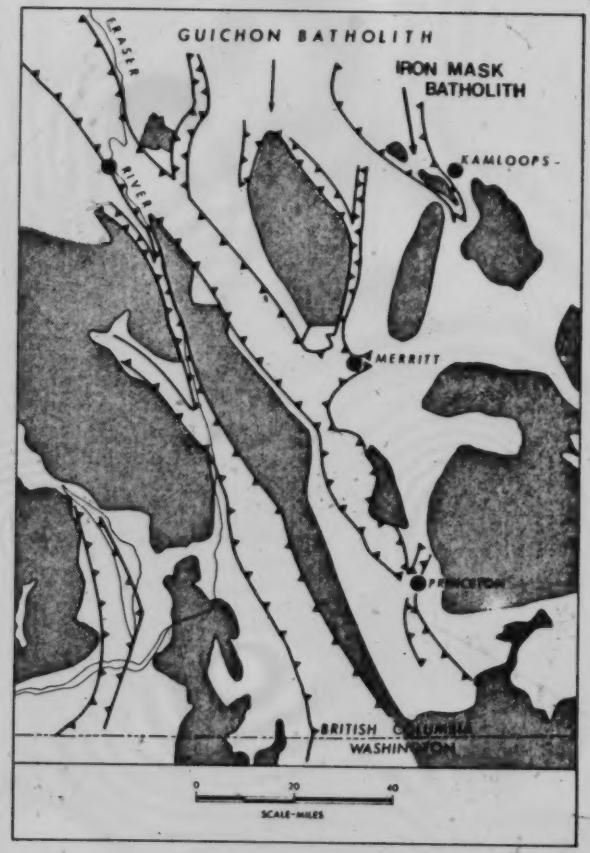


Fig. II - 2b. Major fault and graben development in south-central British Columbia. (After Carr, 1962)

TABLE II - 1

Table of Formations

ERA	PERIOD	EPOCH	GROUP	LITHOLOGY
		Miocene or later		Basaltic lava
			Unconformity	
CENOZOIC	Tertiary	Eocene	Kamloops Group — Tranquille beds	Rhyolite, andesite, basalt with associated tuffs, breccias, agglomerates Conglomerate, sandstone, shale, tuff, thin coal seams
			Kamloops Group — Coldwater beds	Conglomerate, sandstone, shale, coal
			Unconformity	
		Albian	Kingsville Group	Andesite, basalt, agglomerate; tuff, breccia conformity Arkose, greywacke, shale, conglomerate
			Conformity / Unconformity	
	Cretaceous	Aptian	Spences Bridge Group	Andesite, dacite, basalt, rhyolite; tuff, breccia, agglomerate; conglomerate, sandstone, greywacke, arkose
			Fault contact	
MESOZOIC		Albian/Aptian in part Upper Jurassic	Jackass Mountain Group	Greywacke, argillite, arkose, and conglomerate
			Fault contact / unconformity?	
		Lower Cretaceous	Lillooet Group	Argillite, volcanic conglomerate, tuffaceous sandstone, conglomerate
			Not in contact	
		Lower Cretaceous	Brew Group	Argillite, quartzite, conglomerate
			Not in contact	
	Jurassic	Hetangian Sinemurian to Callovian	Ashcroft Group	Shale, conglomerate, sandstone
			Unconformity with Guichon batholith and older rocks	
	Jurassic and Triassic		Guichon, Iron Mask, Central Nicola, Wildhorse Mountain batholiths and other intrusive rocks	Quartz monzonite, quartz diorite, granodiorite; syenite, monzonite, diorite

TABLE II - 1 (cont'd)

ERA	PERIOD	EPOCH	GROUP	LITHOLOGY
		Intrusive contact		
MESOZOIC	Triassic	Karnian and Norian	Nicola Group	Andesite, basalt, agglomerate, breccia tuff; argillite, greywacke, limestone
				Black shale, argillite, phyllite, siltstone, black limestone
		Fault contact, relations otherwise uncertain		
PALEOZOIC	Permian	Guadalupian	Cache Creek Group (western part) — Marble Canyon Formation	Massive limestone, limestone breccia, chert; minor argillite, tuff, andesitic and basaltic flows
		Wolfcampian to Guadalupian	Cache Creek Group (western part)	Basaltic flows, tuff, chert, limestone, argillite
		Not in contact		
	Pennsylvanian and Permian	Morrowan to Guadalupian	Cache Creek Group (eastern part)	Volcanic arenite, argillite, greenstone, phyllite, conglomerate, breccia; minor limestone, basaltic and andesitic flows, amphibolite

investigators have recognized rocks of similar age and lithology throughout British Columbia (Eisbacher, 1974, Fig. 2; Monger, 1972, Fig. 1), and have correlated or placed these sequences with the Cache Creek Group. Most workers assign Mississippian, Pennslyvanian, and Permian ages to the group, though Danner (1968) included some rocks as old as Middle Devonian.

As a regional mappable unit, the Cache Creek Group forms two discontinuous north trending belts. The eastern belt, which is estimated to be 4330 m (Daly, 1915) to 8330 m (Jones, 1959) in thickness, consists of a heterogenous sequence of predominantly clastic rocks which include: argillite, volcanic arenite, greywacke, polymictic conglomerate, and breccia. Basic to intermediate flows and pyroclastics are locally abundant. Limestone, often missing and of local significance, consists of finely crystalline, oolitic, crinoidal, coquinoid, and black argillaceous varieties.

Detailed studies (Duffell and McTaggart, 1952; Trettin, 1961) of the stratigraphy of the western belt of the Cache Creek Group has revealed a somewhat different lithology. The sequence consists of a thick assemblage of interbedded ribbon chert, argillite, basic volcanic flows and tuffs, limestone and ultramafics. In addition, the Marble Canyon Formation, an enormous carbonate mass with an estimated thickness of 2000 m, is recognized only in the western belt.

The base of the group is not exposed in the map-area, and where contacts are observed, the Cache Creek Group has always proven to be older.

2. Nicola Group

Rocks assigned to the Nicola Group, so named by Dawson (1879) from the type area around Nicola Lake, are exposed in the so-called Nicola belt. This

belt can be traced southward from Kamloops Lake to the international boundary. Work by Schau (1970) and Preto (1974, 1975a, 1975b, 1975c) has added greatly to the understanding of the structure and stratigraphy of the group.

The Nicola Group, as applied to the map-area (Fig. II - 1), is regarded as being entirely or mainly Late Triassic in age. Some Nicola rocks in the Aspen Grove area are, however, thought to span the Triassic-Jurassic boundary (Preto, 1974). Contact relationships with the Cache Creek Group are rarely visible and most often very difficult to establish with certainty. Where exposed, the two groups are most often in fault contact (Schau, 1970; Campbell and Tipper, 1971; Preto, pers. comm.). Unconformities have been described by Jones (1959) and Cockfield (1948) and are presently under re-examination (Okulitch and Read, in preparation).

In the type area, Schau (1970) divided the Nicola Group into two cycles consisting of some 7,667 m of complexly bedded flows, pyroclastic, epiclastic, and bioclastic sediments. Each cycle is characterized by a lower, mainly volcanic assemblage, and an upper heterogenous, but mainly sedimentary, assemblage. Preto (1974, 1975a, 1975b), while mapping the Nicola Group in the Aspen Grove and Allison Lake-Misselula Lake areas, distinguished three belts, each of a different and varied lithology and of uncertain correlation. He concluded that the nature and distribution of the Nicola Group in this manner was largely affected by high angle faults.

A black phyllite unit, which is generally restricted to the eastern portion of the map-area has now been dated as Upper Triassic. This unit has been interpreted as an eastern argillaceous facies of the Nicola Group (Okulitch and Cameron, 1975), as well as representing its basal section

(Campbell and Tipper, 1970).

3. Jurassic and Cretaceous Groups

The Jurassic Ashcroft Formation consists of a succession of dominantly pelitic rocks. Boulder conglomerate, arkosic sandstone, together with fossiliferous black shale, form a section estimated to be some 1667 m thick (Duffell and McTaggart, 1952). This unit, which is considered to be Middle to Upper Jurassic in age, rests unconformably on older rocks of the Cache Creek and Nicola Groups. Boulders derived from these underlying groups together form the base of the section. The highest units in the sequence are invariably fine sandstone and black shale.

Sedimentary and volcanic rocks of Lower Cretaceous age are exposed in an extensive northwest trending belt (Fig. II - 1). The sedimentary rocks have been assigned to the Brew, Lillooet, and Jackass Mountain Groups, and the volcanic rocks are included in the Spences Bridge and Kingsville groups (Duffell and McTaggart, 1952). The lithology of these groups has been described in great detail by Duffell and McTaggart (1952) and reviewed later by Jeletzky and Tipper (1968).

Briefly, thick flysch-like assemblages of fine to coarse marine clastic and volcani-clastic rocks comprise the Brew and Lillooet Groups. Sedimentary rocks of the Jackass Mountain Group, considered to be in part Upper Jurassic, consist largely of greywacke, argillite, and boulder conglomerate. A non-marine origin has been attached to parts of this group. The Spences Bridge Group is composed mainly of an enormous accumulation of explosive and flow type volcanic rocks of dominantly andesitic and dacitic composition. This group is conformably, and locally unconformably, overlain by rocks of

the Kingsville Group which form a succession of basaltic and andesitic lavas, tuffs, agglomerates and breccias. The basal member of the group is composed of non-marine clastic rocks.

4. Kamloops Group

The early Tertiary section in the map-area is represented by the Middle Eocene Kamloops Group. The group includes a highly diversified suite of volcanic rocks; andesite, basalt, trachyte, and rhyolite, with a wide range of color, occurring as lenticular flows and thick beds of breccia and minor tuffs. Sedimentary rocks of the group are for the most part conglomerate, sandstone, shale, and lignitic to bituminous coal.

The flat lying basaltic plateau lavas in the northern part of the map-area represent a late Tertiary succession.

5. Plutonic Rocks

The map-area contains several large Mesozoic plutonic bodies of batholithic dimensions. Included in this group are the well known copper producing Guichon, Pennask, and Iron Mask batholiths. Dates for these intrusives are fairly well established (White et al., 1968; Christopher and Carter, 1976) with ages ranging from Upper Triassic to Lower Jurassic. Plutonic rocks of younger ages are present (post-Lower Cretaceous and Tertiary), though they do not form the enormous complex masses of the 200 million year old group. The older plutonic bodies have been classified in a general way on the basis of their lithology (Sutherland Brown, 1969). Quartz monzonite, quartz diorite and granodiorite intrusions, as character-

ized by the Guichon batholith, form one group, whereas syenite, monzonite, and diorite bodies, such as the Iron Mask batholith, comprise a quartz-poor plutonic suite.

The geology of the Iron Mask batholith, which is host to the Afton copper deposit, is considered in greater detail in Chapters III and IV. For descriptions of the other batholiths the reader is referred to the following: Guichon batholith (Northcote, 1969; McMillan, 1976), Pennask batholith (Cockfield, 1948; Rice, 1947; Schau, 1970), Central Nicola batholith (Cockfield, 1948, Schau, 1970), Wildhorse Mountain batholith (Cockfield, 1948).

Ultrabasic bodies, too small to be shown on the map, are associated with rocks of the Cache Creek Group. These rocks are described as serpentinite, serpentinized peridotite and dunite, together with pyroxenite (Duffell and McTaggart, 1952). The age of the rocks are imperfectly known. Much serpentinite in the interior of British Columbia is associated with Cache Creek Group volcanic rocks, and is therefore of probable Permian age. Younger ultrabasic rocks are also present, as they have been described cutting Triassic and Cretaceous rocks (Cockfield, 1948).

C. REGIONAL METAMORPHISM

Monger and Hutchison (1971) have assigned rocks within the map-area to the following two metamorphic units: prehnite-pumpellyite meta-greywacke facies and some zeolite facies rocks, and greenschist facies. Jurassic and younger rocks have not been subjected to regional metamorphism, though Campbell and Tipper (1971) report regionally developed zeolites in Jurassic rocks just north of the map-area.

Rocks of the Triassic Nicola Group have been regionally altered to mineral assemblages which may be assigned to the laumontite, prehnite-pumpellyite and lower greenschist facies (Schau, 1968, 1970). Rocks of the eastern Cache Creek Group contain mineral assemblages characteristic of the greenschist facies and assemblages transitional between prehnite-pumpellyite meta-greywacke and greenschist facies. The western Cache Creek Group contains mineral assemblages of the prehnite-pumpellyite meta-greywacke facies.

In general, as noted by Monger and Hutchison (1971), there is a progressive increase in metamorphic grade from younger to older, presumably more deeply buried strata.

D. REGIONAL STRUCTURE

The structure of the Paleozoic Cache Creek Group, in contrast to younger rocks, is highly complex. These rocks are generally well foliated and exhibit steep, rapidly changing attitudes. This results in part from the nature of the folding, which when observed is isoclinal with fold axes trending in northwest directions. Evidence that the age of deformation in this group was partly pre-Late Triassic, was presented by Okulitch and Cameron (1975).

The structural style in the remainder of the map-area, in contrast to the more highly deformed Cache Creek Group, is characterized by the broad folds and numerous steep faults of the structurally isotropic Quesnel Trough. Schau (1970) demonstrates that this structural picture was evident by mid-Jurassic time.

Faulting has been the dominant agent of deformation (Campbell, 1966; Campbell and Tipper, 1970; Schau, 1970). No widespread regional fold pattern has been discerned for the area, though Carr (1962) suggested that Nicola rocks may have been broadly folded on gentle arcuate axes parallel to earlier regional structures.

Major north to northwest trending faults, generally considered to be deep seated, were probably active as early as mid-Triassic (Preto, 1975b; Campbell and Tipper, 1970) and were the loci of intermittent movement over a long period of time. As a result, long narrow depressed fault blocks or grabens (Fig. II - 2b) became established in Mesozoic and Tertiary time and are considered a characteristic deformational feature of the map-area. Preto (1974) suggests that this pattern in the Aspen Grove area may have been initiated as a rifting process. Elongation of several of the batholiths, recurrent movement on major faults, subsidiary faulting, and tilting of individual fault blocks may all be attributed to the influence of deep-seated faults.

The age of the last recorded deformation is thought to be post mid-Eocene and pre-Pliocene, as the sediments of the Kamloops Group are gently folded and faulted (Schau, 1970).

Chapter III

LOCAL SETTING

A. INTRODUCTION

The Afton copper deposit is situated at the northwestern margin of the Iron Mask batholith, which, as previously discussed, is one of many bodies that intruded the Nicola Group during Triassic-Jurassic time. Originally thought to be a single differentiated pluton (Mathews, 1944), the Iron Mask batholith is now recognized to consist of several successively emplaced suites of rock. Of particular interest is the Cherry Creek suite, which is host to the Afton orebody. The distribution of the Iron Mask rock suites and local geology of the Afton area are presented in Figures III - 1 and III - 2, respectively.

The following descriptions and interpretations are based partly on work by Carr (1956), Carr and Reed (1976), Preto (1972), and Northcote (1974).

B. LOCAL GEOLOGY

1. Cache Creek and Nicola Groups

Andesite and tuffaceous argillite, belonging to the Cache Creek Group, are exposed on the eastern side of Iron Mask batholith in fault contact with the Nicola Group.

Considerable variation exists in regards to the color, texture, and degree of alteration of Nicola rocks around the Iron Mask batholith. They range in composition from basaltic to andesitic, and consist dominantly of flows and pyroclastics with minor interbedded sediments.

Widespread agglomeratic tuff occurs southeast of the batholith

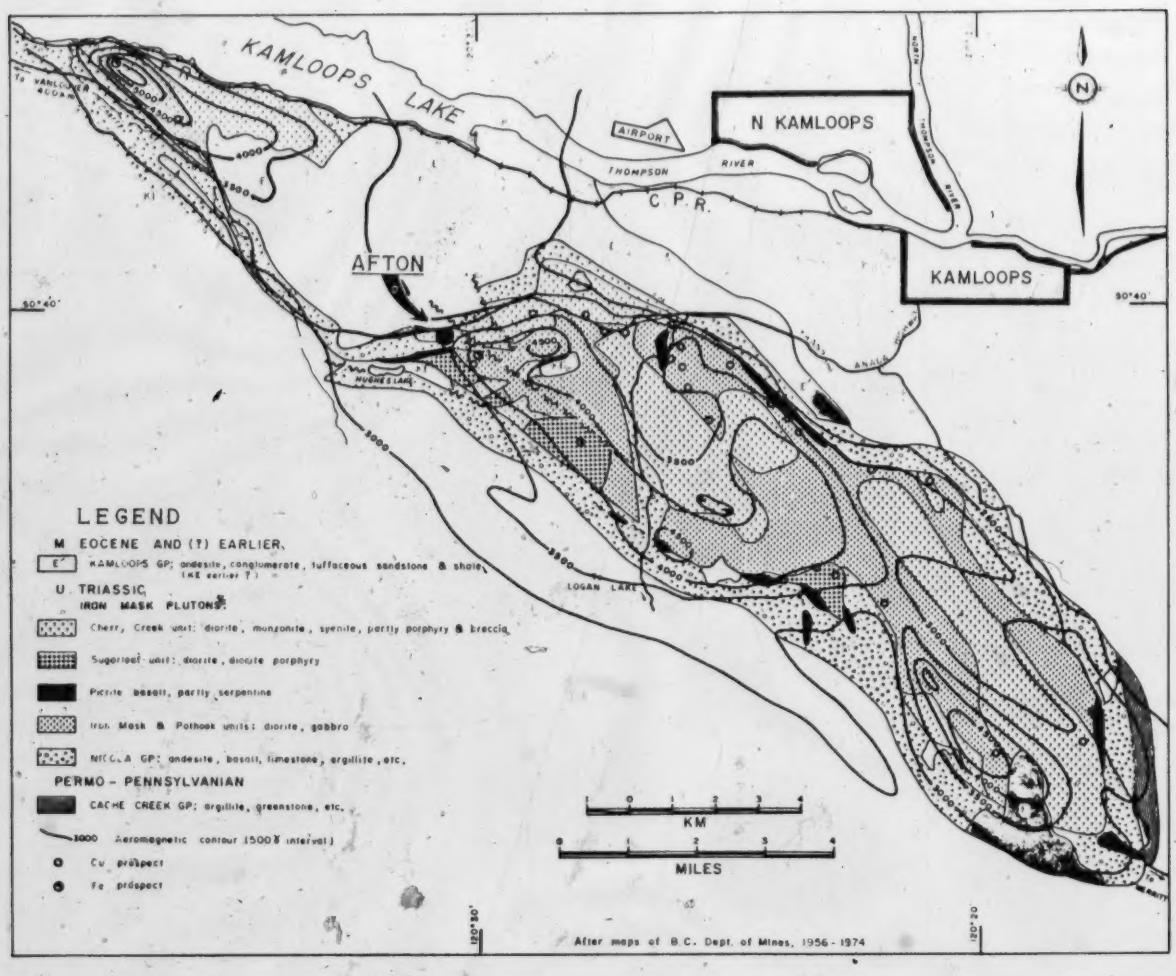


Fig. III - 1. Geologic map of the Iron Mask batholith.(After Carr and Reed, 1976)

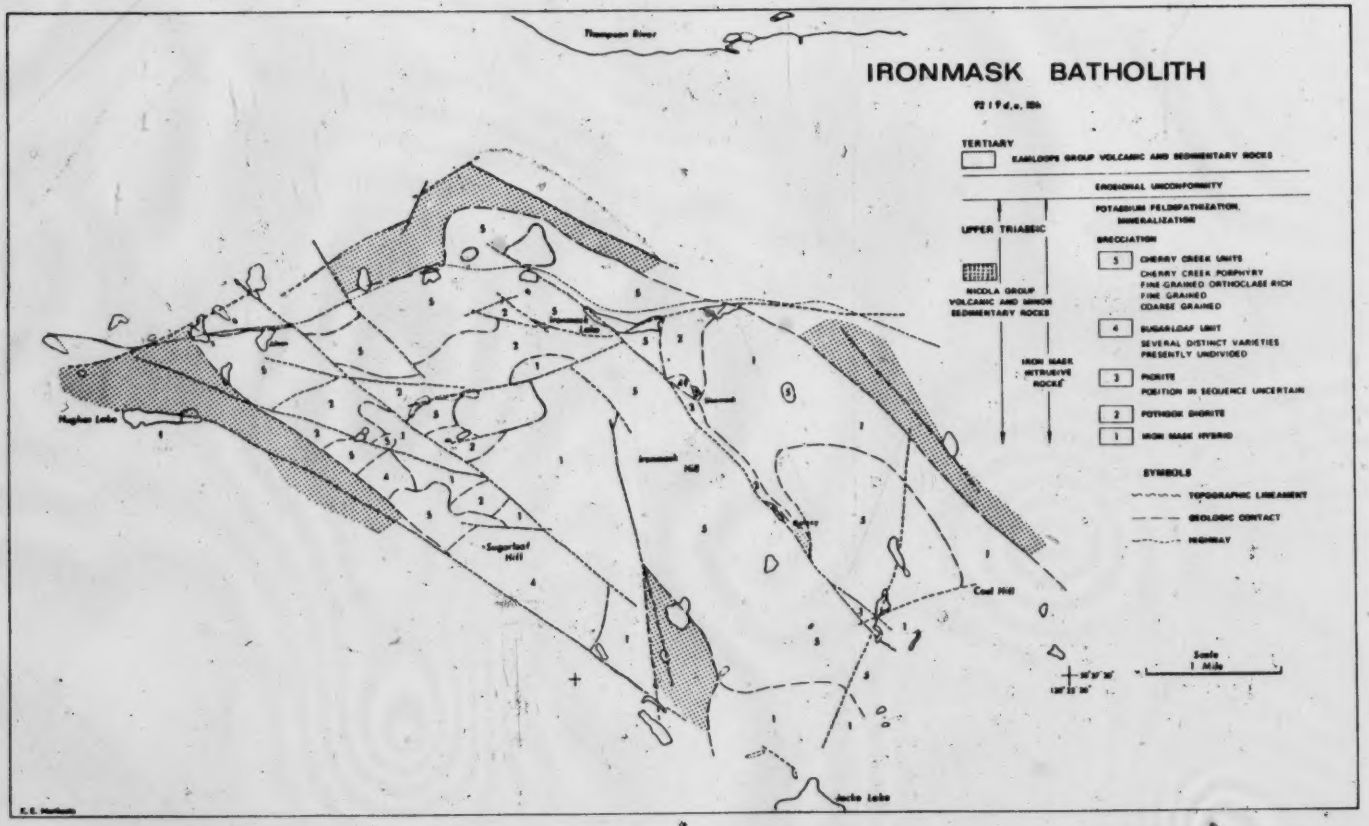


Fig. III - 2. Geology of the northwest portion of the Iron Mask batholith, (After Northcote, 1974)

margin and parallel to the contact with the Cache Creek Group. To the north, flows of grey vesicular andesite predominate. Bedded and massive tuffs are prevalent between Edith and Jacko Lakes to the west, and basaltic pyroclastics are characteristic of the southern part of the area.

Volcanics in the vicinity of the Afton deposit consist principally of pyroclastic types with some interbedded flows. Minor interbedded sediments and sedimentary blocks in breccia are present north of Hughes Lake and northwest of Sugarloaf Hill. Limestone is reported southwest of Sugarloaf Hill(Carr, 1956), and this, together with argillite, is a not commonly observed local rock type.

Rocks described as lahars and tuff breccias (Northcote, 1974) are reported to contain intrusive rock fragments which are identical to rocks of the Cherry Creek suite. The writer observed a similar occurrence of intrusive fragments in Nicola tuffs* and is in agreement with Preto (1975) that a close time and space relationship existed between volcanism and intrusion.

2. Contact Zone

Rocks of the Nicola Group have undergone metasomatism and hydrothermal alteration in response to intrusion of the Iron Mask batholith. The contact zone is irregular and seldom well-defined. Intensity of metasomatism decreases markedly away from the intrusive contacts. Thermal metamorphic affects (sensu stricto) are generally weak as a well developed thermal aureole has not been recognized, and the country rock has not been systematically recrystallized to hornfelses. Secondary mineral assemblages, how-

* See Plate IV - 2E, page 46.

ever, have formed as a result of metasomatism and hydrothermal alteration. Physical conditions of the albite-epidote hornfels facies or lower greenschist facies existed. According to Winkler's limiting conditions for the beginning of the hornblende hornfels facies a maximum temperature of 540°C ± 20°C at P_f = 2000 bars can be assumed to have existed in the contact zone.

Epidote, chlorite, calcite, magnetite, and hematite are often ubiquitous in the contact zone. Apatite, biotite, quartz, albite, and copper and iron sulfides are also present. Distribution of these minerals are related to open spaces as they occur as veins, veinlets, disseminations, and amygdule infillings.

Numerous tongues, dykes, and apophyses have penetrated, and in part dioritized, the Nicola volcanics in the contact zone. These bodies are fine grained and generally related to the younger intrusive phases of the batholith. Mathews (1944) describes albitite dykes which have locally penetrated the volcanics by a process involving replacement as opposed to intrusion.

The contact zone is in effect gradational. It defines an area of intense shearing, dyke intrusion, metasomatism and hydrothermal alteration. Any pre-existing sharp contacts have been obliterated by the above processes.

3. Iron Mask Batholith

The rock suites which comprise the Iron Mask pluton (Fig. III - 1) are all of late Triassic age. Potassium-argon dating of biotite has indicated an age span of 190 to 205 ± 6 million years (Preto, pers. comm.). As a result of subsequently detected errors, a formerly quoted date of 176 million years (Wanless, 1968) is not considered accurate (Preto, pers. comm.).

Considerable variation in texture, grain size, and mineralogy exists

between and within the various rock suites. The majority of the rocks range in composition from basic to alkalic, though some slightly quartz saturated varieties are known.

(a) Iron Mask Unit

The Iron Mask Unit is heterogenous in nature. Rounded and angular fragments of coarse grained gabbro, medium and coarse grained hornblendite, coarse to fine grained diorite, and scattered xenoliths of Nicola volcanics are contained in a diorite matrix. The fragments are of variable size and differ markedly in composition and texture over short distances. Intrusive contact relationships with younger phases are sharp and in part fault controlled. A northwesterly trending recurrent fault system was the dominant structure controlling emplacement of the Iron Mask Unit.

(b) Pothook Unit

Rocks assigned to the Pothook phase are medium to coarse grained and of gabbro-diorite composition. They possess a mean grain size greater than 1.5 mm and are generally non-porphyritic. Calcic plagioclase is the dominant mineral, forming anywhere from 42% to 89% of the bulk composition. Augite and hornblende are proportionately variable, with one often predominating over the other. Biotite and/or chlorite are varietal components together with apatite and magnetite which are present in accessory amounts.

Distribution of the Pothook phase suggests that its emplacement was affected by northwest and northeast trending fracture systems. Contacts with the Iron Mask Unit are in part gradational and together with the low degree of differentiation of both phases, a close genetic and magmatic relationship is implied.

(c) Picrite Basalt

Picritic basalt is structurally part of the Iron Mask batholith though

its genetic relationship to the other intrusive units is unresolved. An Upper Triassic age can be assigned to the picrite basalt as it contains fragments and is cross-cut by units dated as Upper Triassic. Picrite is generally restricted to the structurally weak contact zones at the batholithic margin where it forms steeply dipping lenticular bodies. These bodies appear to have a close spatial relationship to mineralization as exemplified by an elongated dyke-like body, just south of the Afton deposit. Most other copper prospects of the batholith are found within a few hundred meters of this rock type.

Picrite basalt also occurs in non-batholithic rocks north of Kamloops Lake and is intrusive into Nicola volcanics southeast of Jacko Lake (Fig. III - 1). Unaltered rocks from Jacko Lake display a conspicuous porphyritic tendency, with partly serpentinized olivine phenocrysts up to 5 mm in diameter set in a fine grained partly glassy matrix. Pyroxene, with optical properties similar to pigeonite (Cockfield, 1948; Mathews, 1944) occurs as phenocrysts and as a matrix constituent. Magnetite is a common accessory, occurring principally in the groundmass.

Picrite basalt displays various stages of alteration, involving serpentine, chlorite, tremolite, and talc as the principal alteration products. In addition, picrite basalt has suffered a high temperature alteration in which it is converted to a rock consisting largely of pyroxene, hornblende, and biotite transected by garnet veinlets. The alteration of picrite basalt appears to have occurred prior to copper mineralization in the area. Recurring fault movement and subsequent intrusion of microdiorite-micromonzonite are considered responsible for the alteration types (Carr, 1956).

Intrusion of picrite basalt appears to have been dominated by a

northwest trending fracture system. The zones of recurring fracture have more than a local significance as they are thought to occupy faults of a regional system (Carr, 1956; Northcote, 1974).

(d) Sugarloaf Unit

Succeeding the picrite basalt are rocks of the Sugarloaf Unit, which contain abundant inclusions of the earlier phases. The most common varieties are porphyritic microdiorite and fine grained hornblende plagioclase porphyries. Hypabyssal textures, characterized by preferred orientation of plagioclase and mafic minerals, is commonly developed.

Sugarloaf diorite was intruded as elongate bodies, up to 1 km wide, and as narrow dykes. Intrusion of this unit, which is generally restricted to the western margin of the Iron Mask batholith, was controlled by a northwest trending fracture system (Northcote, 1974).

(e) Cherry Creek Suite

The youngest intrusive phase of the Iron Mask batholith is the Cherry Creek suite, which was first recognized as such by E. Livingston in 1960. Rocks of this suite, which are host to the Afton orebody, frame and transect the older units of the Iron Mask batholith. In addition, Cherry Creek rocks comprise the main part of a smaller satellite stock, which is exposed on either side of Kamloops Lake. The Cherry Creek suite will be discussed in greater detail in the following chapter.

4. Kamloops Group

Rocks belonging to the Kamloops Group lie unconformably and in fault contact with rocks of the Iron Mask batholith. They form a diverse sequence of volcanics and non-marine sediments. The sediments, which comprise the Tranquille beds, consist of tuffaceous sandstone and siltstone, tuff, con-

glomerate, and betonitic shale. Basaltic and andesitic flows, agglomerate, together with latite, dacite, and trachyte comprise the volcanic portion.

The Kamloops group attains considerable thickness to the north of the Afton deposit where drilling bottomed out in some 600 m of section. In addition, clastics in the vicinity of Hughes Lake were discovered occupying a narrow fault controlled basin. The expanse of Tertiary cover (Fig. III - 2) is believed to be part of a major depositional basin from which a salient extended southward, covering a part of the Iron Mask batholith (Carr and Reed, 1976).

C. STRUCTURE

The structural setting of the Iron Mask batholith is dominated by high angle faults and zones of recurring fracture, with poorly defined broad folds being of minor significance. These structural elements are consistent with the regional structural pattern discussed in Chapter II.

The Iron Mask batholith is elongated in a northwest to southeast direction, with its axes parallel to the trend of the Nicola country rock. Attitudes, where obtained, indicate that bedding in the Nicola group strikes north 30° to 60° west with moderate dips. Locally, Nicola rocks obtain steep dips, probably indicating tight folding in response to local fault movement. Drag folds, which plunge 30° northwest, are also present.

A northwest trending syncline, the axes of which pass close to Edith Lake, was recongized by Mathews (1944). Cockfield (1948) also documented this structure, postulating that the Iron Mask batholith occupied the eastern limb of the syncline. In contrast, Jones (1959) speculated that the Iron Mask batholith occupied the core of an anticline

which plunges 30° northwest. The presence of an anticline or syncline is not fully substantiated by structural data. Nicola rocks lack secondary foliation and penetrative cleavage and do not appear to have been folded in any systematic way. Regional stress, intrusion, faulting, or combinations thereof could account for the observed folds.

Stress in the Iron Mask area has been predominantly relieved by faulting. Although no major 'through-going' regional faults have been identified, the possible remnants of such features are recognized. The southern terminus of the North Thompson Fault, thought to be related to a principal southward extension of the Pinchi Fault (Campbell and Tipper, 1971, Fig. 5) is located some 38.3 km northeast of Kamloops. The fault may extend from that point southward, into the nearby Vernon map-area (Campbell and Tipper, 1971). In addition, the Quilchena fault zone (Schau, 1970), which extends en echelon from Princeton northward into the North Thompson River valley, may be part of the same system. Faulting to the south and east of the Iron Mask batholith could be related to this system.

A great number of fracture and shear zones of diverse orientation attest to the complex fault system in the area. North, northwest, northeast, and west trending zones of weakness are present. Intensity of faulting is greatest at the batholithic margin, and as previously discussed, faults are largely responsible for distribution of the various Iron Mask rock suites. Normal faults, block faults, oblique and cross-faults are present. They generally have steep dips and are believed to be the surface expressions of deep seated faults. Age relationships are difficult to work out. Faults which have controlled emplacement of the Iron Mask suites are presumably of an Upper Triassic or earlier age.

Slickensides, with several different attitudes may be present on any one fault plane, and attest to the recurrent fault movement throughout time.

The development of local fault controlled depositional basins is consistent with the regional structural style. Eocene Kamloops Group strata occupy a graben at the northern border of the batholith. Other partly fault-controlled basins, such as the Hughes Lake basin, are also present. As the basal sections of these basins are not exposed, the true ages are unknown. Some may be as old as late Triassic or Middle Jurassic.

A major proportion of the Iron Mask rocks are synchronous as they conform to the northwest structural grain of the enclosing Nicola group. The general northwest elongation of the Iron Mask batholith is at some variance with the more northerly regional trend of the Nicola belt to the south. Carr and Reed (1976) illustrate that this northwest cross-structure is substantiated by isomagnetic contours, and delineates an area some 35 km long by 10 km wide. In an earlier work, Carr (1962) showed the Iron Mask batholith occupies an extensive northwest trending graben feature which may constitute a separate fault block from the area to the south.

D. ECONOMIC MINERALS

Numerous occurrences of copper together with economically significant amounts of gold, silver, iron, and mercury, are found within the vicinity of the Iron Mask batholith. Lead and zinc are virtually unknown, and molybdenite is rare. The following descriptions are only brief summaries of the occurrences and for more detailed information the reader is referred to works by: Carr (1956), Cockfield (1948), and the annual reports of the B.C. Minister of Mines.

Deposits of mercury occur in a north to northwest trending belt, some 13 km wide by 37 km long, part of which straddles the west end of Kamloops Lake. The principal metallic mineral is cinnabar, accompanied by lesser and varied amounts of malachite, azurite, tetrahedrite, stibnite, and realgar.

The deposits occur in faulted, fractured, sheared, and brecciated rocks of Mesozoic age. The origin of these deposits and their relationship to Mesozoic or Tertiary volcanism, is unknown. They are the only mercury deposits in British Columbia not obviously related to the regional systems of the Pinchi, Manson, and Fraser-Yalakom faults.

Significant occurrences of magnetite are found at several localities within the Iron Mask batholith. Magnetite is concentrated in zones of sufficient size to warrant mining. The Glen Iron Mine, situated 10 km northwest of the Afton copper deposit, produced prior to 1902, some 15,000 tons of magnetite ore. A second prominent zone of magnetite is intimately associated with the Afton deposit.

The principal occurrence of magnetite in the Iron Mask batholith is of the vein-type, though there is a continuum from large lenticular and tabular bodies, through pods, veinlets to low grade disseminations. The lenticular and tabular bodies grade laterally into stockworks. Banding has been locally developed in some of the larger bodies (Godwin, pers. comm.).

The veins are composed of fine to coarse grained magnetite with variable but often significant quantities of apatite. The larger bodies at the Glen Iron Mine are almost always characterized by apatite zones up to several meters wide. These magnetite-apatite deposits clearly postdate the major magmatic phase as they invariably cross-cut the Iron

Mask intrusive suites.

The copper deposits (e.g. Pothook, Iron Mask, Copper King) of the Iron Mask batholith are believed to be genetically related to the Afton deposit, and are only distinguished from it by their smaller size, lower primary grade, and general lack of supergene enrichment. All intrusive suites of the Iron Mask batholith, including picrite basalt (Godwin, pers. comm.) contain copper mineralization.

Chapter IV

MINE GEOLOGY

A. INTRODUCTION

The Afton orebody is situated within the Cherry Creek phase of the Iron Mask batholith (Fig. IV - 1). Locally, Nicola volcanics have been subjected to weak copper mineralization and Kamloops Group rocks, though post-mineral in age, structurally form part of the deposit. In this chapter, details of the mine geology (including host rock lithology, nature of the orebody, zonation, and structure) will be discussed. Descriptions and observations are based upon the writers' examination of outcrop, diamond drill core, and petrographic slides. Sixteen diamond drill holes, totalling some 4,900 m of section were logged and sampled (Fig. IV - 2). Core samples (BX- size) were selected at 5 m intervals, or wherever any megascopic change was observed in the alteration pattern, mineralization, or rock type. Subsequent to field work, 120 polished, polished thin, and thin sections were studied. All drill core was slabbed and stained for potassium and sodium feldspar.

B. HOST ROCKS

1. Cherry Creek Suite

Several petrographically distinct Cherry Creek varieties are host to the Afton orebody. Specific varieties have been distinguished by their composition, texture, and grain size, which of course reflects the environment and conditions of crystallization. In contrast to the older Iron Mask suites, rocks of the Cherry Creek suite are generally finer grained and display conspicuous porphyritic and micro-porphyritic textures. Locally

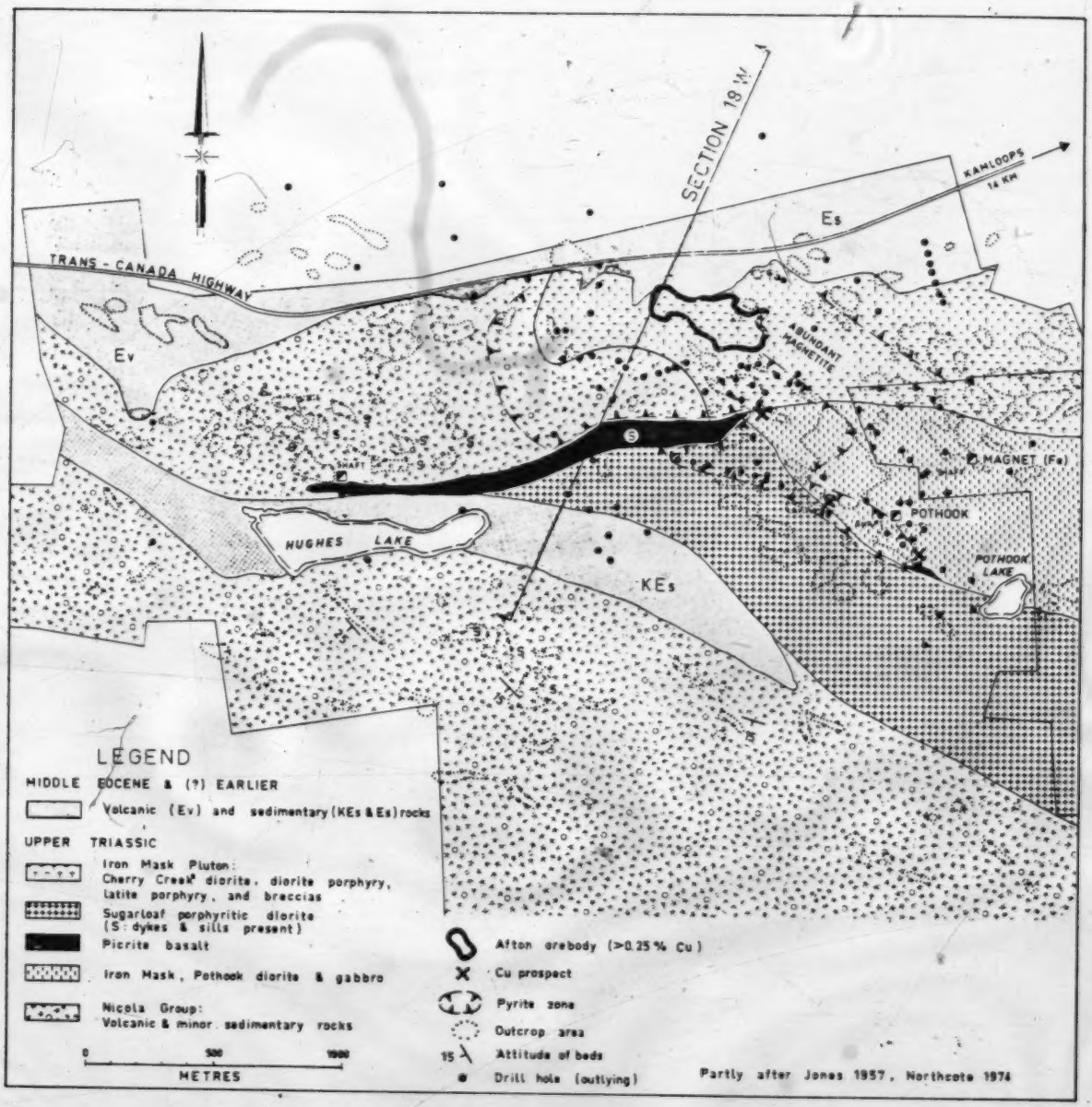


Fig. IV - 1. Local geology of the Afton copper deposit. (After Carr and Reed, 1976)

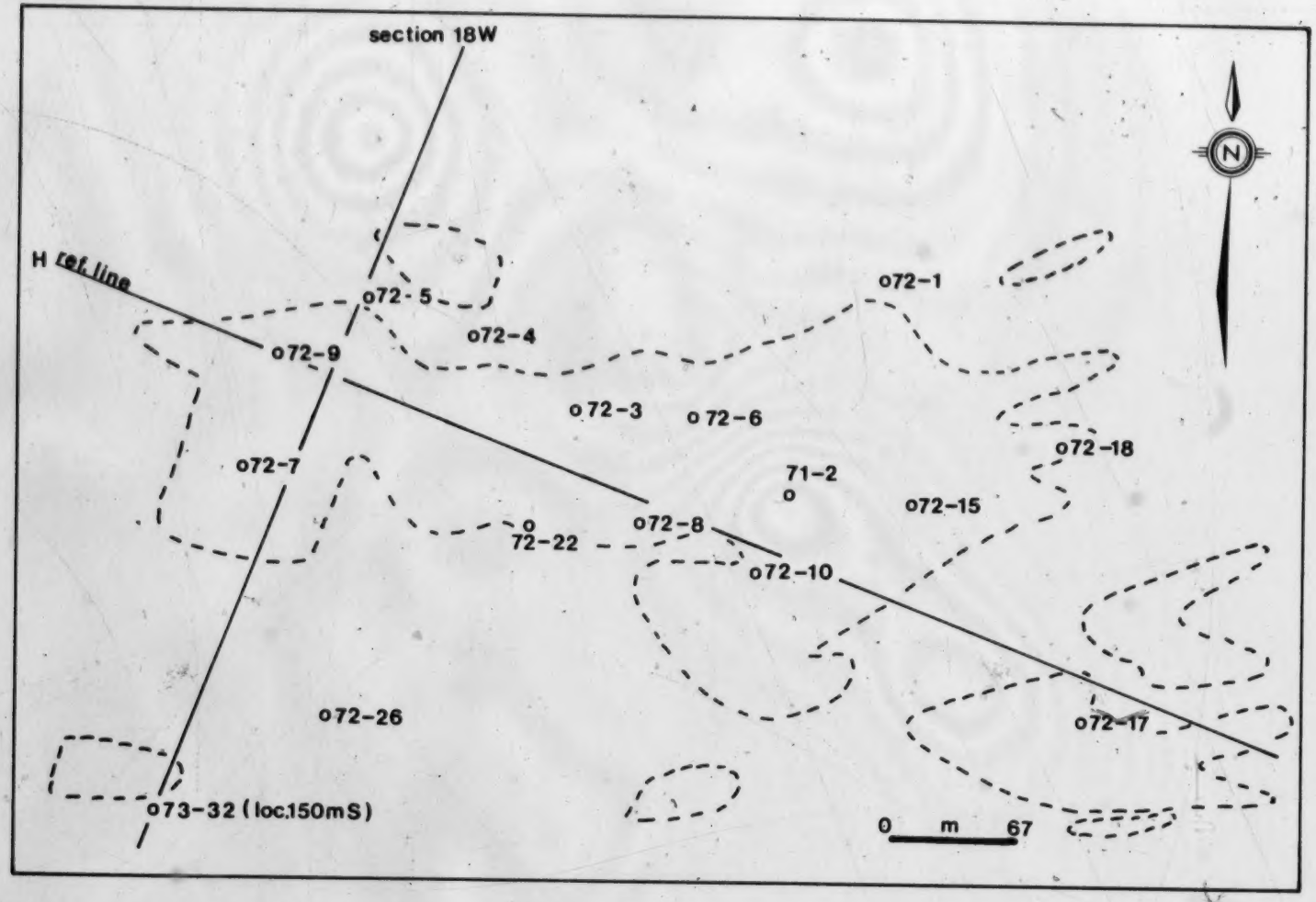


Fig. IV - 2. Location map of diamond drill holes selected for core sampling. Dashes outline the orebody at the 600 metre level.

hydrothermal alteration has completely destroyed rock textures, but in the majority of samples original textures were discernible even in some of the highly altered portions of the orebody (Plate IV - 1A).

Composition, which was determined by optical and staining techniques, ranges from diorite through monzonite to syenite. Introduction of potassium feldspar and other secondary minerals during hydrothermal alteration has modified original rock compositions. However, in many of the sections examined, the writer was able to determine the original rock type. Photomicrographs of the Cherry Creek rocks are presented in Plates IV - 1 and IV - 2. A petrographic outline follows.

(a) Diorite - Microdiorite (Plate IV - 1B)

Non-porphyritic medium and fine grained rocks of diorite composition form a relatively minor textural variant of the Cherry Creek suite. They are most abundant in the footwall of the orebody and are encountered over short distances elsewhere. In hand specimen, these rocks are mesocratic, being of a green to greyish-green color. Grain size for the coarser variety averages from 1.0 to 2.0 mm with some grains attaining up to 5 mm in diameter.

In thin section, Cherry Creek diorite and microdiorite display well developed hypidiomorphic granular and microgranular textures. A sub-fluxion texture, characterized by crudely aligned plagioclase was also occasionally observed in these rocks. Subhedral plagioclase of andesine to oligoclase composition comprises 60% to 70% of the total composition. The remaining proportion includes variable quantities of biotite, hornblende, and augite, together with accessory sphene, apatite, and magnetite. Minor amounts (rarely exceeding three percent) of interstitial alkali feldspar and quartz was also observed.

(b) Cherry Creek Syenite and Monzonite (Plate IV - 1C)

Cherry Creek syenite and monzonite have been intruded as dyke and dyke-like bodies with known widths generally not exceeding 14 m. In hand specimen, these rocks are characterized by a pink coloration due to the presence of potash feldspar and fine grained disseminated iron-oxides. Conspicuous inclusions of green microgranular diorite are occassionally observed in these rocks. The inclusions, which seldom exceed a few centimeters in diameter, are indistinguishable from the aforementioned Cherry Creek microdiorite. Grain size, though somewhat variable, averages 1.5 to 2.0 mm with some potash feldspar grains attaining 4 mm in the lone dimension.

In thin section the Cherry Creek syenite and monzonite display a holocrystalline trachytoid granular texture. Grain boundaries are ragged, mutually penetrating, and impart a hypidiomorphic texture to the rock. A faint porphyritic tendency may be locally developed, however, a fluxion texture, defined by the parallel alignment of feldspar, is more typical.

In Cherry Creek syenite, orthoclase and microperthitic orthoclase composes up to 70% of the total rock composition. Anhedral plagioclase, which is poikilitically included and embayed by alkali feldspar, accounts for 15% to 20% of the total. Augite seldom exceeds 15% and magnetite together with apatite are common accessories. With an increase in plagioclase content, Cherry Creek syenite grades into rocks of monzonite composition.

Cherry Creek syenite and monzonite are considered by the writer to be a minor textural variant of the Afton host suite of rocks. Some bodies are but weakly mineralized and altered and may be inter- and/or post-mineralization in age.

(c) Cherry Creek Porphyries

Rocks displaying porphyritic and microporphyritic tendencies are the most volumetrically significant and widely distributed textural variety of the Afton host rock suite. The majority of the intrusive rocks examined by the writer were classified as porphyries. These rocks have been emplaced as a complex series of intrusions which are irregular and dyke-like in form. The exact dimensions of individual bodies of porphyry are as yet imperfectly known. They appear to be in the order of several tens of metres wide, though larger masses may be present. Contact relationships among individual varieties are both sharply cross-cutting (Plate IV - 1D) and gradational. As the orebody is stripped, the geometry of the various phases will undoubtedly become better known.

Cherry Creek porphyries were divided by the writer into three distinct grain size groupings. The first two groupings include rocks in which phenocrysts and a porphyritic tendency were megascopically visible with the two groupings being distinguished by the numerical limitations on the grain size of the phenocrysts. Rocks in which phenocrysts attained average dimensions of 1.5 mm or greater were classified, according to their composition, as diorite, syenite, or monzonite porphyries. Finer grained rocks in which the phenocrysts averaged 1.0 mm in diameter were classified as microdiorite, micromonzonite, and microsyenite porphyries. The nature and composition of the phenocrysts in this group could not be ascertained megascopically, hence the use of the term 'micro'. A third group of porphyries are so fine grained that the porphyritic texture was only apparent microscopically. Phenocrysts in these rocks generally averaged between 0.3 to 0.5 mm in diameter. Depending on the composition, these fine grained porphyries were classified as

andesite, latite, or trachyte porphyries.

Several distinct variations of the porphyritic textures are recognized within the Cherry Creek porphyries. The procedure used in deriving Cherry Creek textural nomenclature is outlined in Appendix IV.

(i) Cherry Creek Microdiorite Porphyry (Plate IV - E, IV - F)

Porphyries of diorite composition are the most commonly observed host rock to the Afton copper deposit. These rocks are generally grey to greenish grey in color with more leucocratic types representing the altered equivalents. A megascopic porphyritic texture is generally evident in these rocks, though the composition of individual grains is never apparent in hand specimen.

In thin section, most Cherry Creek microdiorite porphyry displays a hypidiomorphic holocrystalline intermediate groundmass texture. A microvitrophyric texture, in which a small amount of glass is present in the groundmass, was observed in the occassional specimen. All variations of the porphyritic texture (as outlined in Appendix IV) are present in the Cherry Creek microdiorite. The most frequently encountered textures are however, the trachytoid and 'non-orientated' porphyritic textures.

Phenocrysts, which generally account for 60% of the total rock components, are subhedral to anhedral, with corroded grain margins. A complexly twinned and occasionally zoned plagioclase is the most abundant phenocryst mineral, with hornblende and pyroxene (augite) together composing 30% to 40% of the total phenocryst material. Alkali feldspar rarely exceeds 15% of the total. Phenocrysts in rocks of diorite composition are generally in the size range of 1.0 mm and as previously discussed are called microdiorites. With an increase or decrease in phenocryst grain size, these rocks grade into compositionally equivalent and less frequently encountered diorite and andesite

porphyries.

The most commonly observed matrix of Cherry Creek microdiorite appears as a mosaic of strongly interlocking anhedral grains (see Plate IV - 2 B). The matrix texture is microcrystalline microgranular, with an average grain size never exceeding 0.1 mm. A common feature of the groundmass components is that they appear to have corroded and embayed the larger phenocrysts. This feature is believed to have resulted from reaction between earlier formed phenocrysts and late stage melt during final crystalization. The matrix is typically feldspathic, consisting essentially of an intermediate plagioclase and subordinate alkali feldspar. Quartz was rarely observed.

(ii) Cherry Creek Micromonzonite-Latite Porphyry and Microsyenite-Trachyte Porphyry (Plate IV - 1G, IV - 1H, IV - 2A)

Cherry Creek micromonzonite and latite porphyries are the second most abundant host rocks to the Afton orebody. These rocks are lighter in color than microdiorite porphyry and are distinguished from the latter by their pink color.

These rocks display well developed intermediate to high groundmass porphyritic textures which are most typically of the trachytoid or semi-trachytoid variety. Most other variations of the porphyritic texture (Appendix IV) are also present in these rocks.

Micromonzonite and latite porphyries consist of approximately equal proportions of plagioclase and alkali feldspar phenocrysts set in a microcrystalline groundmass rich in alkali feldspar. The groundmass in a number of specimens displayed an aplitic or 'sugary' texture. With an increase in the alkali feldspar content these rocks grade into less abundant microsyenite and trachyte porphyries.

(d) Cherry Creek Breccias (Plate IV - 2C, IV - 2D)

The distribution of Afton Cherry Creek breccias are imperfectly known, partly due to the inherent problems of drill core sampling. Hence rocks described as intrusion breccias may be more widespread than is realized. Two types of breccia (with the exclusion of fault breccia) are recognized within the Afton deposit.

Intrusion breccia : it consists of a heterogenous mixture of Cherry Creek rocks in a fine grained highly feldspathic groundmass, generally of syenitic composition. A microporphyritic texture has been observed in the groundmass. Rock fragments are subangular to subrounded and rarely exceed a few centimeters in size. Breccias of this nature, which are associated with the Afton orebody, have been described by Carr and Reed (1976) and elsewhere in Cherry Creek rocks by Carr (1956) and Preto (1967).

Crackle breccia : it is intimately associated with alteration and copper mineralization. 'Crackle' breccia consists of altered fragments of various sizes and shapes which appear to have been 'rafted' apart and healed by copper bearing solutions, now represented by veins, veinlets, and microveinlets. In contrast to intrusion breccia, the fragments do not appear to have moved for any appreciable distances, and where determined, are composed of only one rock type (i.e. microdiorite, micromonzonite and latite porphyries).

2. Nicola Volcanics (Plate IV - 2E)

Afton Cherry Creek porphyries and related rocks have intruded a predominently pyroclastic succession of Nicola volcanic rocks. The contact zone, as defined, is sheared and steeply dipping to the south (Fig. IV - 3). The volcanics are green or red to purple in color and have been subjected to

PLATE IV - 1

PHOTOMICROGRAPHS OF CHERRY CREEK ROCKS

Afton Copper Deposit, B.C.

A. Sample D.D.H. 72 - 22 (- 133 m)

Highly altered Cherry Creek porphyry, displaying relict texture typical of advanced stages of alteration. Dark areas represent former ferromagnesian sites which have been converted to a chlorite-carbonate-epidote-sulfide mixture. (Transmitted light, open nicols)

B. Sample D.D.H. 72 - 22 (- 71 m)

Fine grained equigranular to low groundmass Cherry Creek diorite displaying sub-fluxion texture. Black areas are disseminated chalcopyrite. (Transmitted light, nicols X)

C. Sample D.D.H. 72 - 10 (- 371 m)

Medium grained Cherry Creek syenite displaying well developed fluxion texture, defined by the parallel alignment of feldspar. Specimen is weakly sericitized. (Transmitted light, nicols X)

D. Sample D.D.H. 72 - 3 (- 100 m)

Photomicrograph shows intrusive contact between two contrasting Cherry Creek varieties. Upper portion of photo shows microdiorite with hypidiomorphic equigranular texture. Below contact, in lower half of photo, is microporphyritic low groundmass latite porphyry. (Transmitted light, nicols X)

E. Sample D.D.H. 73 - 32 (- 537 m)

Cherry Creek microdiorite to micromonzonite porphyry showing hypidiomorphic trachytoid intermediate groundmass texture. Note very fine grained aplitic groundmass texture. (Transmitted light, nicols X)

F. Sample D.D.H. 72 - 8 (- 337 m)

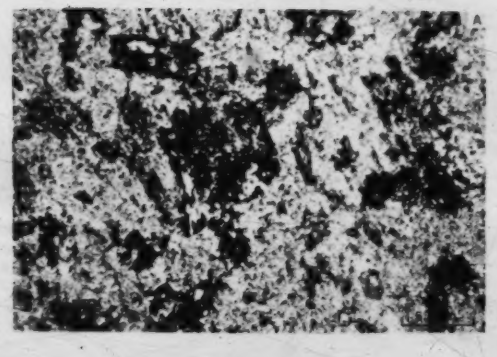
Cherry Creek microdiorite with high groundmass trachytoid texture. Veinlet (black area) consists of chalcopyrite-bornite-epidote. (Transmitted light, nicols X)

G. Sample D.D.H. 72 - 22 (- 283 m)

Cherry Creek latite porphyry with seriate porphyritic texture. Opaques are fine grained disseminated pyrite. (Transmitted light, nicols X)

H. Sample D.D.H. 73 - 32 (- 549 m)

Cherry Creek micromonzonite porphyry with intermediate groundmass and non-orientated alkali feldspar and plagioclase set in a fine grained intermediate aplitic groundmass. (Transmitted light, nicols X)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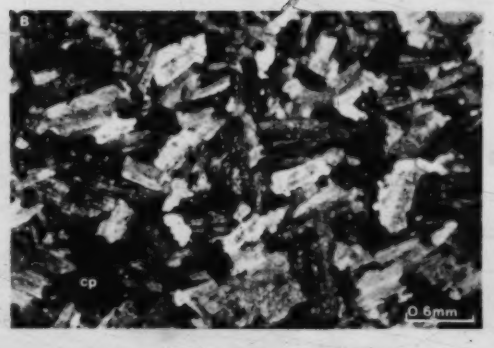
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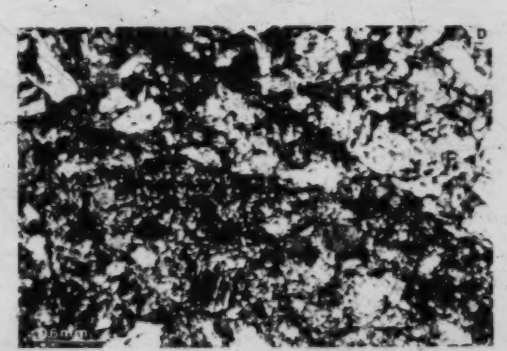
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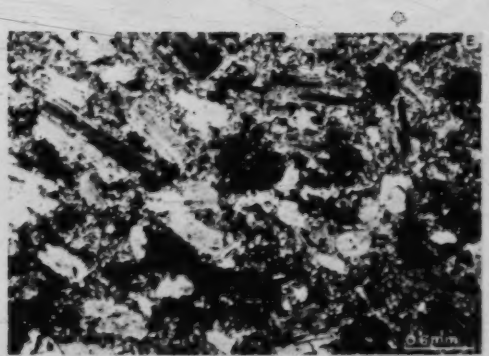
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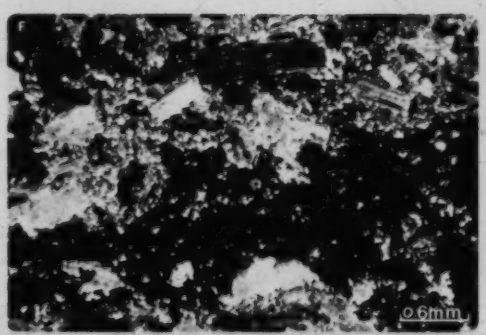
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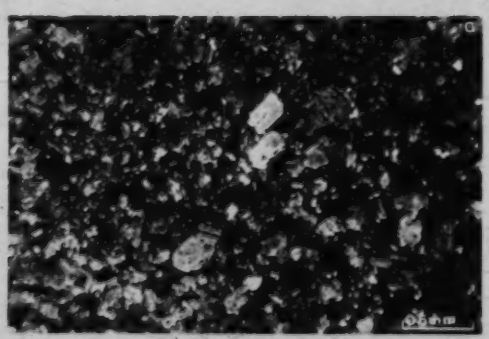
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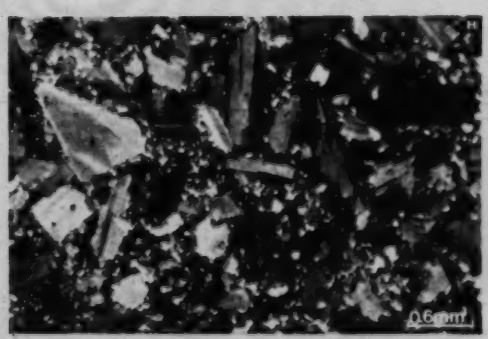
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PLATE IV - 2

PHOTOMICROGRAPHS OF CHERRY CREEK,
NICOLA, AND KAMLOOPS GROUP ROCKS

Afton Copper Deposit, B.C.

A. Sample D.D.H. 73 - 32 (- 400 m)

Typical fine grained Cherry Creek latite porphyry with intermediate biotized groundmass. Black areas are disseminated bornite-chalcopyrite. (Transmitted light, nicols X)

B. Sample D.D.H. 73 - 32 (- 132 m)

Photomicrograph shows typical groundmass texture of relatively unaltered Cherry Creek microdiorite porphyry. Note strongly interlocking anhedral tendency of matrix components. Matrix consists of plagioclase with lesser alkali feldspar. (Transmitted light, nicols X)

C. Sample D.D.H. 72 - 26 (- 81 m)

Photomicrograph shows small subrounded fragment (bx) composed of fine grained equigranular diorite set in a microporphyritic matrix of monzonitic composition. (Transmitted light, nicols X)

D. Sample D.D.H. 73 - 32 (- 549 m)

Photomicrograph shows Cherry Creek crackle-breccia which is characteristic of the hypogene ore zone. Note that the small fragments (bx) have been rafted apart by the ore-bearing solutions. (Reflected plane light)

E. Sample D.D.H. 73 - 32 (- 35 m)

Photomicrograph shows Nicola tuff which is mildly propylitized and contains disseminated pyrite (opaques). Area in upper left portion of photo resembles altered Cherry Creek porphyry. (Transmitted light, nicols X)

F. Sample D.D.H. 72 - 1 (- 145 m)

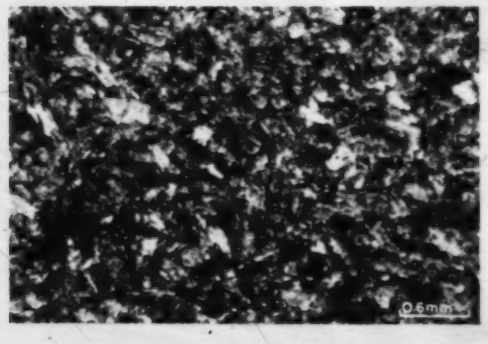
Photomicrograph shows healed fragments of unaltered Kamloops Group latitic lava and post-supergene calcite cockade structure. (Transmitted light, nicols X)

G. Sample D.D.H. 72 - 22 (- 106 M)

Kamloops Group porphyritic andesite, which, in contrast to the Upper Triassic Nicola volcanic rocks, is unaltered. (Transmitted light, nicols X)

H. Sample D.D.H. 72 - 5 (- 60 m)

Photomicrograph shows Kamloops Group tuffaceous siltstone, with carbonate matrix (dark fine grained areas). Small igneous fragment (bx) in centre of photo may have been derived from underlying Nicola or Cherry Creek rocks. (Transmitted light, nicols X)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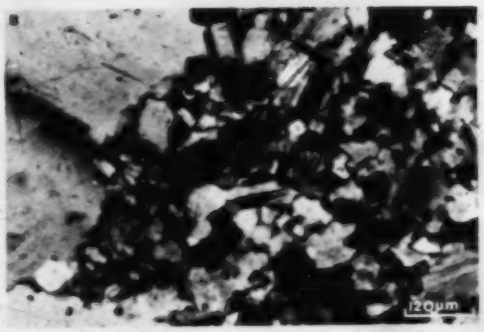
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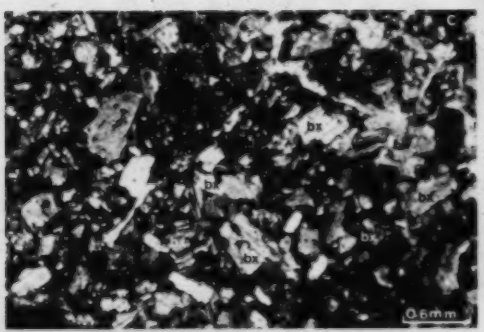
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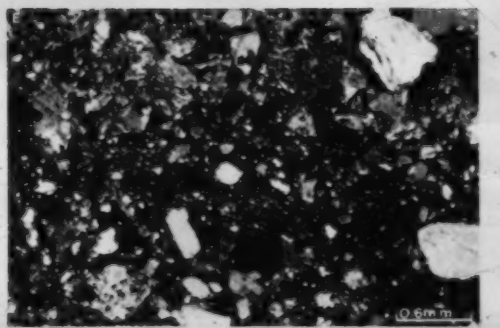
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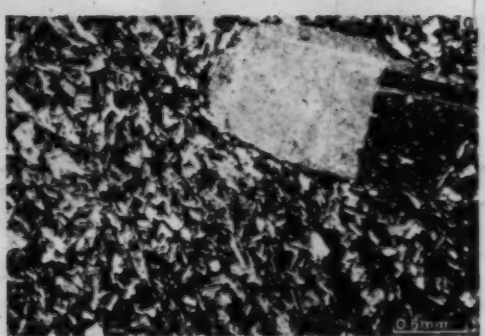
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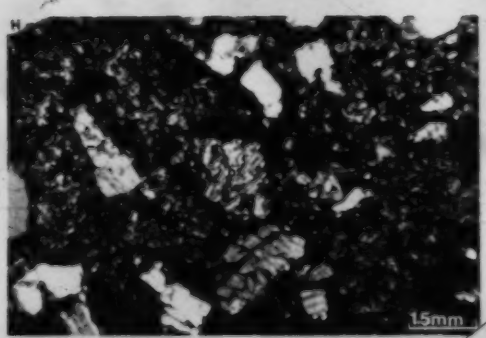
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varying degrees of alteration and mineralization. Alteration was helpful in distinguishing these rocks from the younger Tertiary volcanic rocks in the area. Inclusions of Nicola country rock were observed in a number of drill holes. Several of the inclusions were identified as recrystallized Nicola tuffs together with minor flow rock. These, together with the Nicola rocks described in the preceding chapter, are believed to define a very complex volcanic sequence within the immediate area of the Afton deposit.

3. Kamloops Group (Plate IV - 2F, IV - 2G, IV - 2H)

Middle Eocene volcanic and sedimentary rocks are structurally part of the Afton orebody. They occur in fault contact with mineralized Cherry Creek rocks, and as a flat overlying unconformity. Preto (1972) speculates that the wedges of Tertiary strata that are now observed within the Cherry Creek rocks have been emplaced in their present juxtaposition by a combination of landslides and normal block faulting. Light colored siltstones, calcareous sandstones, tuffs, together with porphyritic and fine grained andesitic to latitic lavas are recognized. Healed breccias, in which the foregoing rock types have been brecciated and cemented by calcite and quartz, are occasionally observed. Latite porphyry dykes, thought to be related to Tertiary volcanism, have been described by Carr and Reed (1976). These younger rocks are not altered and are devoid of any copper mineralization.

C. THE AFTON OREBODY

1. Ore Grade and Mining Techniques

Drilling, which was completed in 1974 and totalled 49,045 meters, has

outlined an orebody with a drill-proven ore reserve of 30.84×10^6 tonnes of 1.0% copper, 0.58 ppm gold and 4.19 ppm silver, with a stripping ratio of 4.2:1. The ore reserve estimate is based upon a cutoff grade of 0.25% copper.

The deposit will be mined by open pit methods with the ore being milled and smelted on-site. Approximately 87% of the copper will be recovered by the 6,300 tonnes per day milling process which will provide a metallic concentrate grading 50% copper. The smelter will produce blister copper exceeding 99% purity.

2. Orebody Geometry

Because the Afton orebody is a stockwork type orebody, any description as to shape is necessarily a description of a mineralized mass of rock that exhibits copper values in excess of a certain arbitrary cutoff grade of 0.25% copper. The orebody (Fig. IV - 3) by this definition is a deltoid tabular body that strikes approximately N70°W, with an average dip of 55° to the south (Fig. IV - 4). The dip is somewhat variable, changing from 35° in the west, up to a maximum of 80° in the centre, and flattening to 30° in the eastern protion of the deposit. In plan, (Fig. IV - 5), the deposit measures 520 m long, averages 90 m in width, and has a known depth of 600 m. Viewed from the south, the deposit approximates a right-angled triangle, with its apex defining the deeper western portion of the deposit. Due to an increase in width and depth to the west, approximately half the proven reserves occur in the western third of the deposit.

The orebody however occurs within a much larger mass of mineralized and altered ground. The Nicola country rock has been affected up to distances at least in the order of 700 m beyond the 0.25% copper cutoff margin. In

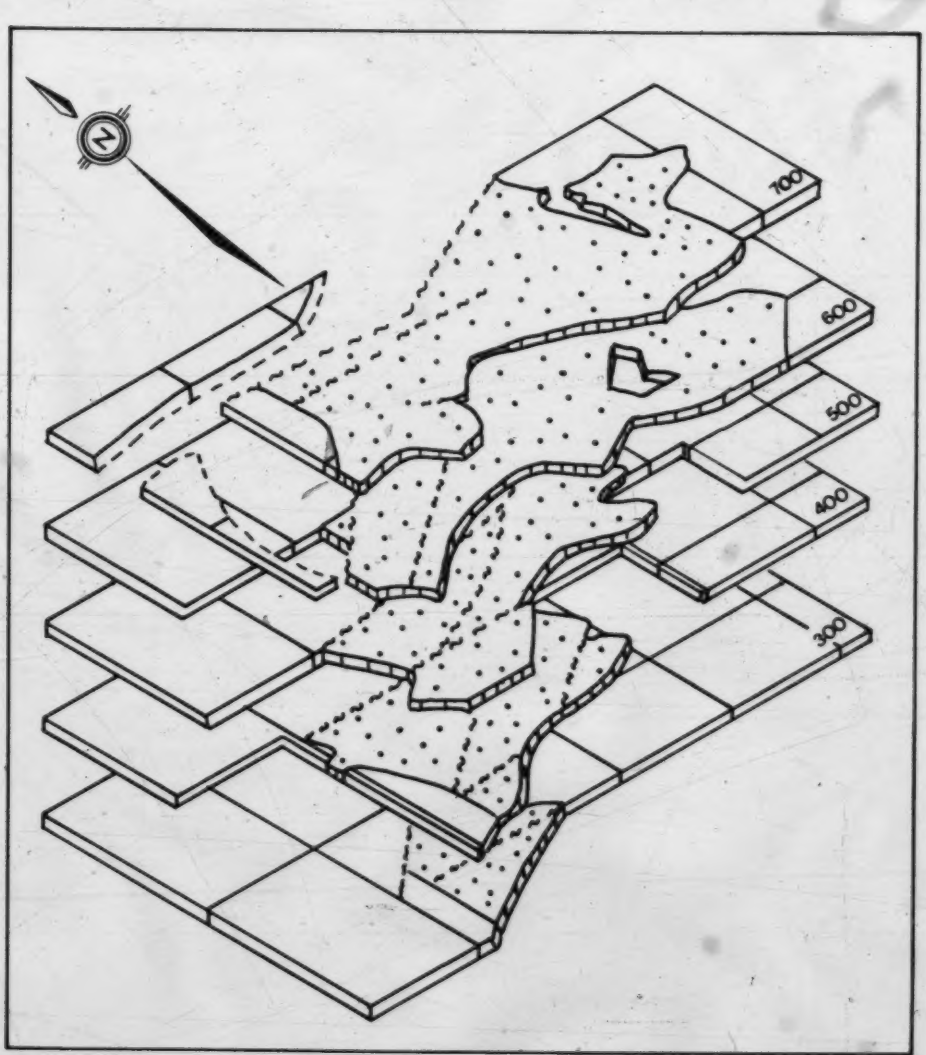


Fig. IV - 3. Three dimensional view of the Afton copper deposit (dotted sections) looking north-east. Elevation in metres above sea level. (Modified from Afton Mines Ltd., Annual Report, 1973)

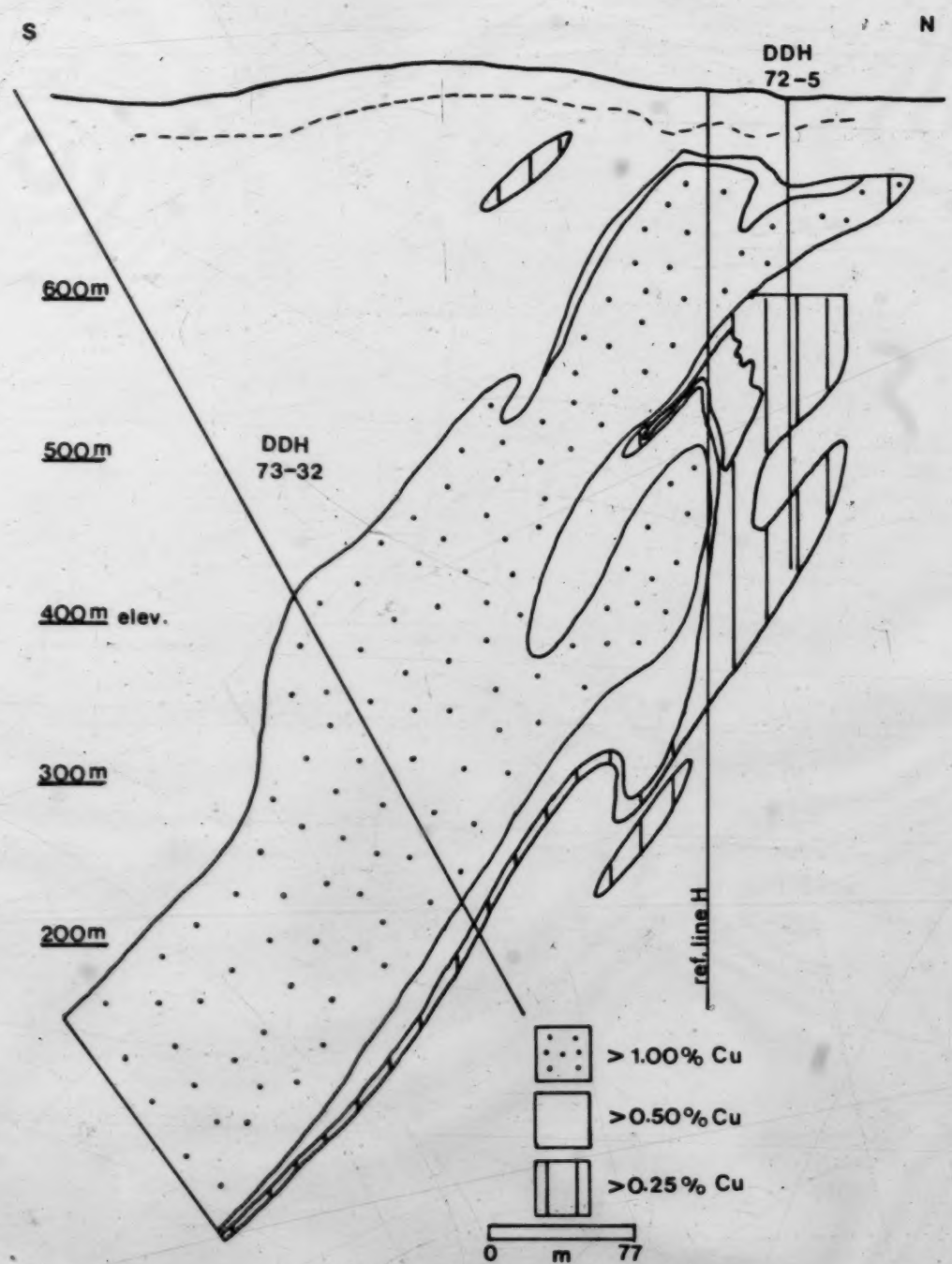


Fig. IV - 4. Vertical section (section 18 W) of the Afton copper deposit looking west. (Modified from Afton Mines Ltd., Annual Report, 1972)

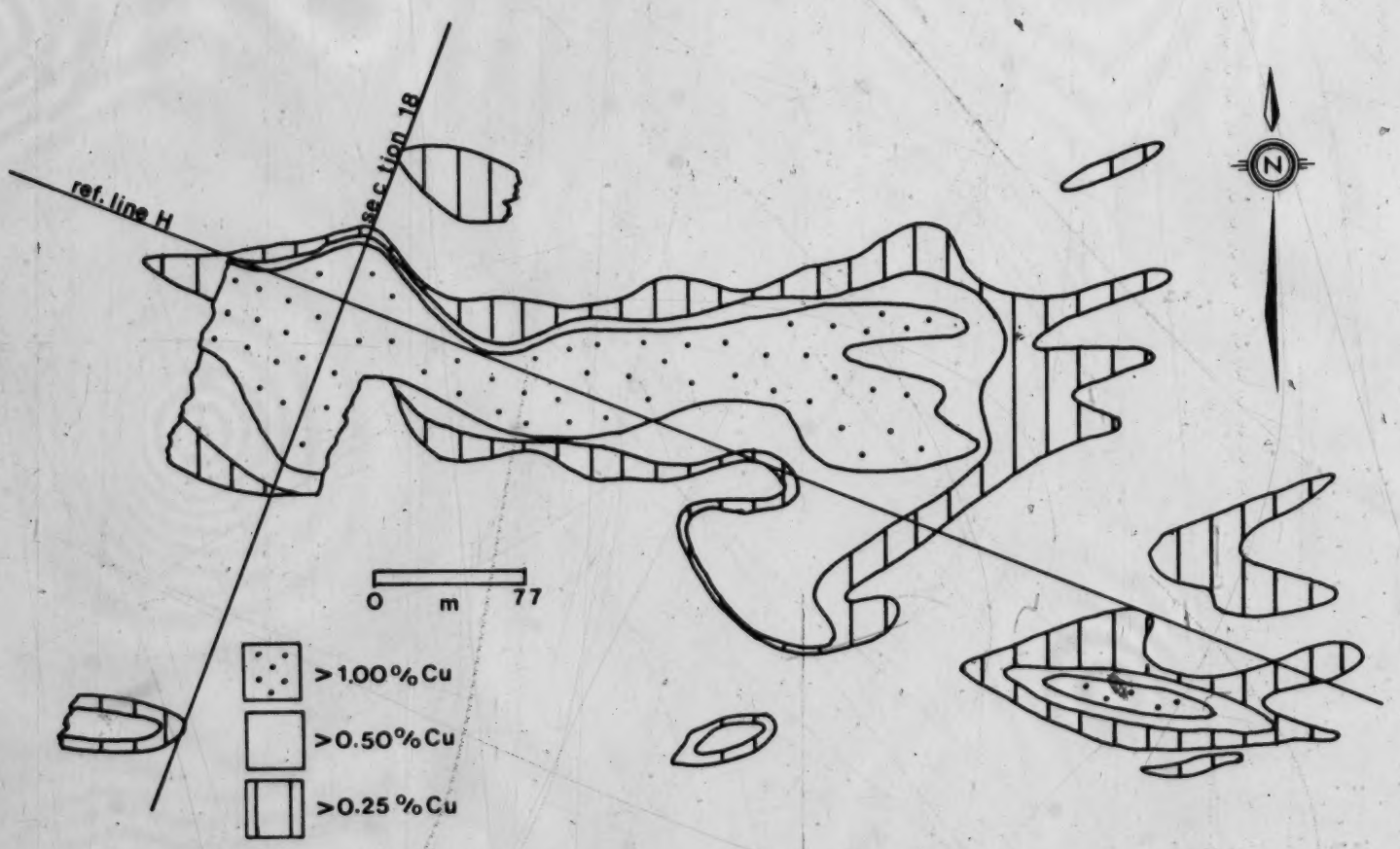


Fig. IV - 5. Plan section of the Afton copper deposit at the 600 metre level. (Modified from Afton Mines Ltd., Annual Report, 1972)

addition, the geometry of the orebody is much more complicated than was revealed in the previous statement. Detailed sections (Fig. IV - 6, IV - 7) compiled by Teck geologists illustrate these complexities. In plan, the orebody is amoeboid in form, with several lensoid and irregular shaped mineralized zones occurring peripherally to a much larger mass. These smaller 'satellite' zones represent shoots that connect to the main orebody or define distinct mineralized pods.

Down dip, the deposit is only completely defined in the eastern portion. To the west, the deepest drill holes indicated that above cutoff grade copper is still present at greater depths. A high grade ($\geq$1% Cu) core is present within the orebody and is generally restricted to the central and western protions of the deposit.

3. Mineral Zonation

Large scale mineral zonation, defined by the presence of a particular mineral or mineral assemblage, exists within and around the Afton orebody proper. The following zones are recognized: hypogene zone, supergene zone, magnetite zone, and pyritic halo.

A 1.5 km long pyritic halo (Fig. IV - 1) flanks and encloses the Afton orebody. The hanging wall, which is composed for the main part of Nicola volcanics with a lesser volume of Cherry Creek rocks, is characterized by a zone of strong pyritic mineralization. This zone may be up to 700 m wide. To the southeast of the orebody, the pyritic halo approximates a semi-circle from which an irregular salient narrows and projects southwesterly to where it flanks the smaller Pothook deposit.

The eastern portion of the deposit is superimposed by a northwest trending magnetite zone which is some 300 m wide and 800 m in length. The

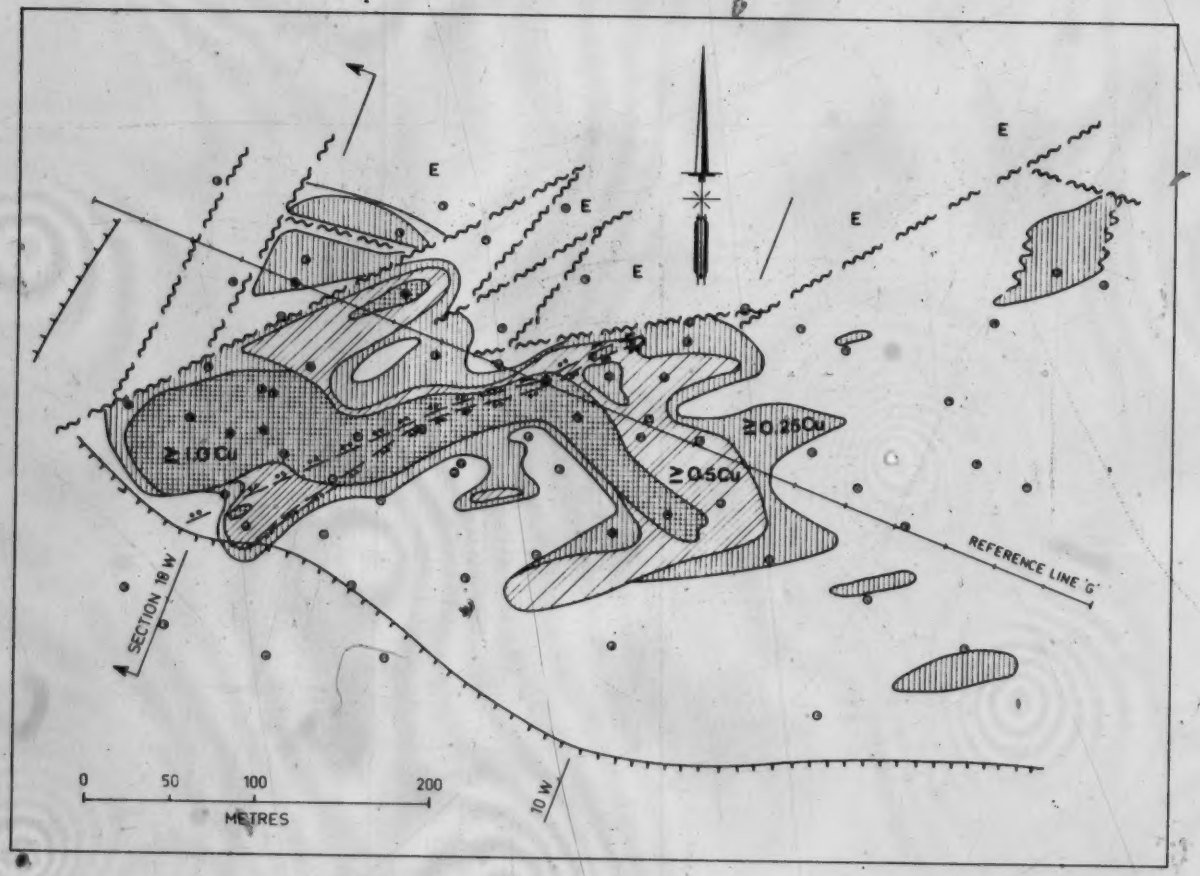


Fig. IV - 6. Plan of mineralization (values in %) at the 488 metre level of the Afton copper deposit. (After Carr and Reed, 1976)

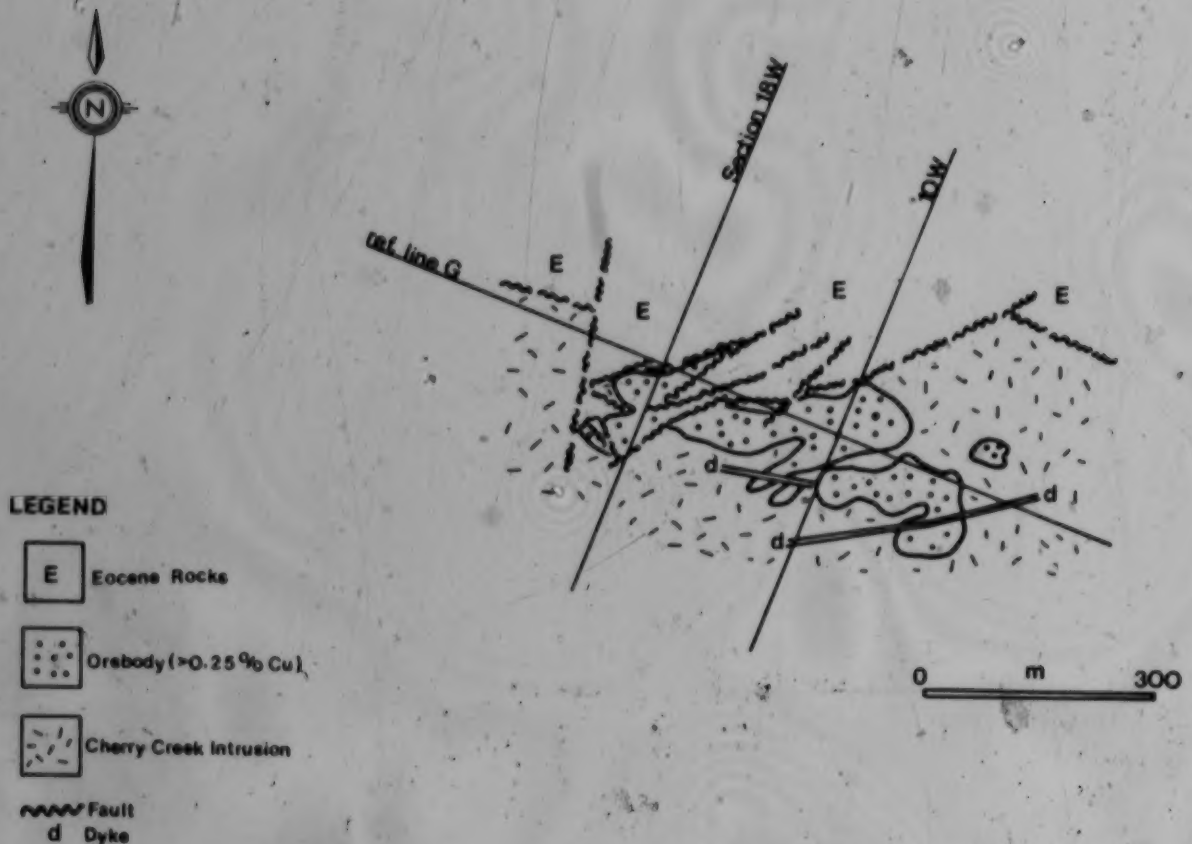


Fig. IV - 7. Schematic plan of late faults at the 567 metre level of the Afton copper deposit (after Carr and Reed, 1976).

magnetite zone is flanked on both sides by the pyritic halo, with the Afton deposit situated at its northwestern extremity.

The Afton deposit contains both primary (hypogene) and secondary (supergene) ore minerals. The hypogene zone, which is composed mainly of bornite and chalcopyrite, is restricted to the lowermost portions of the deposit, generally below 500 m elevation in the east and 250 m elevation in the west. The supergene zone, which is characterized by the presence of native copper, forms an irregular but sharp boundary with the underlying hypogene zone. It is more extensively developed in the western portion of the deposit and appears to plunge in this direction from a point midway along strike of the orebody. Windows or relicts of hypogene mineralization occur locally within the supergene zone and likewise septa of the supergene zone often penetrate deeply into the hypogene zone.

A leached cap is all but lacking in the Afton deposit with ore grade material usually encountered in the uppermost bedrock material. As was suggested by Preto (1972), Pleistocene glaciation is thought to have removed any leached capping that may have existed. In addition, portions of the supergene zone, particularily in the eastern part of the deposit, have been removed by glaciation.

Details of the ore mineralogy, gangue mineralogy, and wallrock alteration will be presented in Chapters V and VI.

D. STRUCTURE

A detailed structural synthesis of an orebody that is unstripped and partly covered by overburden is most difficult. Accordingly, structural

details of the deposit are imperfectly known. From the information that can be gathered, however, it is ascertained that structure has had a marked influence on the distribution of host rocks, localization of the orebody, and development and preservation of the supergene zone. The numerous fault breccias and gouge zones which are observed in drill core and outcrop attest to a complex history of deformation in the area. Important easterly and northeasterly trending faults are thought to have localized emplacement of the Afton host Cherry Creek suite (Preto, 1972; Northcote, 1974). The easterly trend and southerly dip of the orebody is considered to be an expression of this fault system. In addition, magnetite veins, thought to be pre and inter-hypogene stage, conform to an east-west trend with steep dips to the south.

The intimate and extensive fracturing of Cherry Creek rock was a necessary prerequisite to the formation of the Afton orebody. Intensity of both hypogene and supergene mineralization can be related to intensity of deformation.

The post-hypogene stage structure is somewhat better known than the pre-mineral fault and fracture pattern. The majority of the recognized faults either postdate the hypogene event or are post-mineral in age. Some may represent reactivated earlier structures.

Teck geologists recognize the following three fault sets: Strike faults (W or WNW), oblique faults (NE or ENE) and cross faults (NNE). These sets have been delineated largely as a result of their effect on barren Eocene strata (Fig. IV - 6, IV - 7) which has been imbricated and faulted into position within the orebody. Known maximum displacement of Eocene rock is in the order of 100 m. Both normal and reverse movements

are reported (Carr and Reed, 1976).

Faulting and attendant fracturing and shearing are also considered important factors in controlling the distribution of secondary minerals. Deep penetration of supergene salients within the hypogene zone is observed only in intensely sheared and fractured rock. This is particularly evident in the western portion of the deposit where the base of the supergene zone reaches its deepset level. The westerly plunge of the supergene zone is considered to be largely a result of a higher density of fractures and shears in the western half of the deposit. Preto (1972) speculates that normal movement on cross-shears or breaks at the time of Tertiary graben formation in the area may have depressed the western part of the orebody with respect to the east. In addition, the entire block of ground occupied by the Afton deposit may have been depressed in a stepwise fashion as a partly fault controlled Tertiary basin developed just to the north. The net result of the post-mineral faulting and graben development was that the area occupied by the Afton deposit was depressed and covered by a northward thickening Tertiary section and ultimately preserved from later glaciation.

Chapter V

THE ORE MINERALS

A. INTRODUCTION

The metalliferous minerals of the Afton deposit occur as native metal, sulfides, oxides and sulfosalts. They form distinct assemblages which, as was briefly discussed in the preceding chapter, are distributed in various zones which constitute the orebody. In this chapter, characteristics of the ore minerals, including nature of occurrence, detailed zonation pattern, and mineralogy, will be presented.

B. MODE OF OCCURRENCE

The ore minerals occur as disseminations, veins, veinlets, and microveinlets. Hence, by definition, the Afton deposit can be classified as a porphyry copper deposit as the copper-bearing minerals occur in disseminated grains and veinlets through a large volume of rock. Veinlet controlled mineralization accounts for several orders of magnitude greater of ore-grade material relative to disseminated ore minerals. Metalliferous minerals in veinlets and in disseminations are often present together, though a crude zonation in the mode of occurrence of the hypogene minerals is evident.

At depth in the footwall (see Fig. IV - 4), and below the 0.25% Cu cut-off, hypogene minerals occur as finely disseminated grains. This zone grades vertically into a slightly higher grade zone in which disseminated mineralization predominates over veinlet and microveinlet controlled mineralization. This submarginal ore zone, which represents some 70 m of section, then grades abruptly into a zone comprising the high grade core ($\geq$1% Cu). Here the order is mainly reversed, with a dense network of veinlets and microvein-

lets exceeding disseminated minerals in abundance. Noteworthy is the absence of any prominant veins. Locally, within the core, where copper grade is lower, disseminated type mineralization may equal or exceed veinlet related mineralization. The high grade core then passes into a peripheral pyritic halo, in which the hypogene minerals form disseminations and veins. The volume of vein pyrite in the halo equals or exceeds that of disseminated pyrite. The magnetite zone, which straddles the eastern termination of the orebody, is characterized by veins with subordinate disseminations.

Lowell and Guilbert (1970), in describing the zonation of mineralization in porphyry copper deposits, recognized a similar progressive gradation in the mode of occurrence of the hypogene minerals. They considered the sequence from the deepest disseminations, through veinlets and disseminations to peripheral veins to be a characteristic feature of porphyry copper deposits.

The progressive gradation in the nature of the hypogene minerals at Afton reflects the behavior of host and country rock in response to the mineralizing solutions. During hypogene mineralization, the bulk of the host Cherry Creek suite is believed to have acted as an incompetent mass, as it did not support any large through-going veins. Rather, channelways for the ore-bearing solutions were provided by an intricate system of fractures or any other permeable structures that were present. The groundmass of the Cherry Creek porphyries was particularily favourable for localizing the ore-bearing solutions. Under the microscope, ore and gangue often appear as a complex network laced throughout the groundmass. This feature is illustrated in Plate V - 1A. Where disseminated type mineralization

takes the form of isolated grains, not exhibiting any obvious spatial relationship to channelways, the hypogene minerals are often preferentially concentrated at the loci of ferromagnesian minerals. The pseudomorphs of such minerals, pyroxene and amphibole in particular, are represented by their alteration products with or without the metalliferous mineral (Plate V - 1B). In low groundmass porphyries, and rocks displaying equigranular textures, disseminated metalliferous minerals tend to be localized interstitially at grain boundary junctures. Less commonly, cleavage and twin planes have provided access to the ore-bearing solutions.

The mode of occurrence of the supergene minerals is similar to that of the hypogene minerals. Veinlets and disseminations are characteristic. Supergene ore-bearing solutions were in part localized by the same structures which controlled hypogene mineralization. In addition, as was previously discussed, renewed shearing and fracturing superimposed on these earlier structures further provided access for the supergene solutions during Eocene diastrophism.

C. SUPERGENE AND HYPOGENE ORE ZONATION

The known hypogene and supergene metalliferous minerals of the Afton deposit are listed in Table V - 1A. The observed sequence of ore deposition at Afton is not so much a sequence of individual minerals as a sequence of assemblages. The common and minor mineral assemblages are listed together in Table V - 1B.

Pronounced vertical zoning of both hypogene and supergene mineral assemblages is observed throughout the Afton orebody. The deepest penetrations of the hypogene zone have revealed a deep level zone of dominant

TABLE V - 1 - A

Hypogene and Supergene Minerals of
the Afton Copper Deposit, B.C.

Hypogene Minerals	Supergene Minerals
Chalcopyrite	Native Copper
Bornite	Chalcocite
Pyrite	Hematite
Tetrahedrite-Tennantite	Goethite
Magnetite	Covellite
Hematite	Cuprite
Marcasite	Tenorite
Digenite	Malachite
Chalcocite	Azurite
	Chrysocolla
	Jarosite
	Conichalcite

TABLE V - 1 - B

Recognized Mineral Associations of
the Afton Copper Deposit, B.C.

Common Mineral Associations

Chalcopyrite - Bornite
Bornite - Chalcocite
Chalcopyrite - Tetrahedrite-Tennantite
Bornite - Chalcopyrite - Pyrite
Pyrite - Chalcopyrite
Bornite - Chalcocite - Chalcopyrite
Pyrite - Magnetite
Magnetite - Hematite
Marcasite - Chalcopyrite
Magnetite - Chalcopyrite
Chalcocite - Digenite - Bornite
Native Copper - Cuprite
Native Copper - Hematite

chalcopyrite mineralization. Chalcopyrite in this zone is always several orders of magnitude more abundant than bornite. Locally, minor tetrahedrite-tennantite is present. With an increase in the bornite to chalcopyrite ratio, this zone grades into a zone in which bornite is the dominant copper-bearing mineral. A bornite-chalcopyrite-pyrite assemblage is locally present. Chalcocite, which typically makes its first appearance in the bornite-chalcopyrite zone, becomes more prominent relative to an increase in the bornite to chalcopyrite ratio. Hence, a zone of bornite-chalcocite mineralization overlaps and persists above a bornite-chalcopyrite zone. The copper-bearing zones are encompassed by a lean peripheral pyrite zone. Subordinate chalcopyrite, together with marcasite and hematite, are locally encountered in this zone. Within the halo the pyrite to chalcopyrite ratio is estimated to be in excess of 40:1.

A gradual transition from hypogene zonation to supergene zonation occurs throughout the orebody. The transition, which is characterized by a change from bornite-chalcocite to chalcocite-native copper mineralization, takes place within vertical distances varying from 33 to 100m. In detail, the lower limit of the supergene blanket zone is highly irregular. Native copper generally appears at some point above chalcocite, or is otherwise coincident with it. Where metallic copper persists to the base of the chalcocite blanket, a narrow zone ($\sim$10 m) of native copper, chalcocite, and bornite is observed. Native copper is rarely associated with chalcopyrite.

The native copper to chalcocite ratio, which is in part a function of the intensity of oxidation, typically increases up dip from the first appearance of native copper. High ratios of native copper to chalcocite as well as the highest grade copper intersections of the deposit are encountered within a native copper oxidation zone. The zone of oxidation, defined largely by the

presence of hematitic limonite, in effect encloses the zone of supergene native copper mineralization. The zonal pattern developed during hypogene and supergene ore formation is illustrated schematically in Figure V - 1. Descriptions of the various ore textures follow.

D. ORE MINERALOGY

Descriptions and associations of the hypogene and supergene minerals are considered in this section. Most of the metalliferous minerals were identified microscopically in polished and polished thin sections. The electron microprobe was used to determine or confirm minerals that could not be positively identified otherwise.

1. Hypogene Metalliferous Minerals

(a) Chalcopyrite-Bornite

Chalcopyrite and bornite are the principal copper-bearing hypogene sulfides. They are locally present as isolated grains, separate from one another, but more typically occur together, with one mineral usually dominating a particular zone within the orebody. The total volume of bornite to chalcopyrite (as ascertained from the drill sections examined) approximates a 1:1 ratio. A cautionary note is included as this ratio (due to the effect of supergene processes) may differ from that which existed at the time of hypogene ore formation.

The principal modes of occurrence of chalcopyrite and bornite are as disseminations within the altered host rocks and as veinlets and microveinlets. The majority of the observed veinlets are discontinuous over short distances, with the sulfides present as intermittant disseminations and irregular masses. The sulfides were never observed along the entire length of the veinlets. Less commonly the pair occur as coarse blebs and irregular

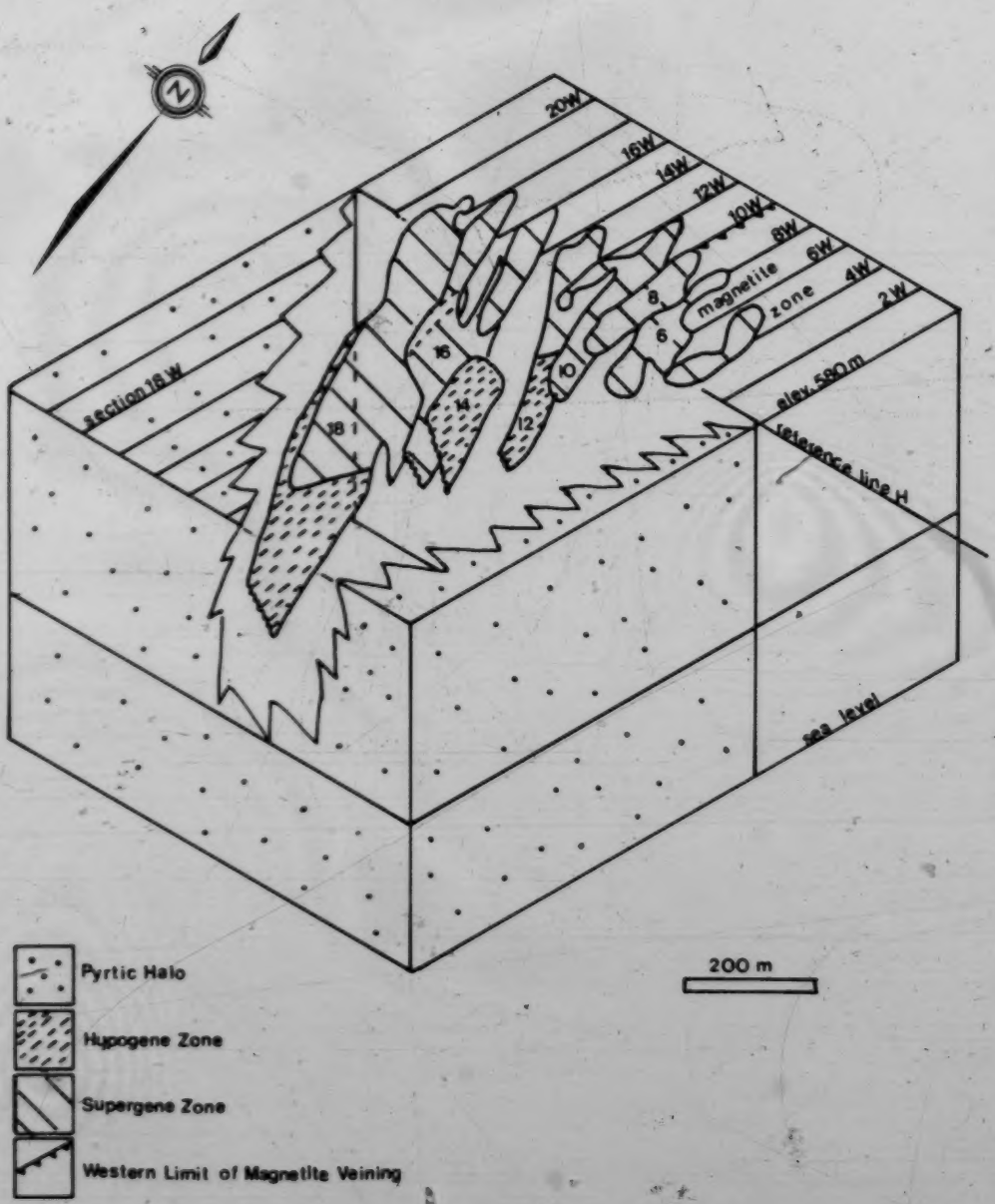


Fig. V - 1. Supergene and hypogene zonation of the Afton copper deposit, B.C. (Partly after Carr and Reed, 1976)

'porous' forms ($\geq$1.0 cm in diameter). Bornite and chalcopyrite are characteristically fine to medium grained. Average grain size is in the order of 1.0 mm, though variations in size from a few microns up to a centimeter may be observed in the same petrographic slide. Grain shape is hypidiomorphic to allotriomorphic, without well defined crystal outlines.

The textural interrelationships of hypogene bornite and chalcopyrite are presented in Plate V - 1C, V - 1D, V - 1E, V - 1F . The following relationships were observed:

(i) Chalcopyrite and bornite display a mutual boundary relationship in which the intergrowth is separated by a smooth mutually penetrating boundary. Replacement and exsolution features are not present and the order of deposition is never evident via this relationship.

(ii) Chalcopyrite occurs within host bornite as orientated microscopic lamellae, lenses, spindles, and wedge-like structures. These forms may be isolated within the host, partly protrude from a grain boundary, or transect the host as a 'pseudovein'. Locally, chalcopyrite occurs as narrow continuous rims around bornite.

(iii) Bornite displays a similar relationship with chalcopyrite as the host mineral. It commonly occurs as irregular blebs and patches within and at chalcopyrite grain margins. Flame-like structures and 'pseudoveins' of bornite cross-cutting chalcopyrite are also observed. Oriented lamellae and spindles of bornite in chalcopyrite were not observed.

(iv) An unusual texture, in which microcrystalline bornite inclusions together with tetrahedrite-tennantite form

'atoll-like' structures and narrow seams within chalcopyrite was observed in the occasional specimen (Plate V - 1G).

It should be noted that the aforementioned textures are not restricted to any particular ore horizon, but rather the pair exhibit a diversity of relationships within narrow spatial limits (i.e. within the same petrographic slide).

(b) Tetrahedrite-Tennantite

Tetrahedrite-tennantite occurs sporadically throughout the hypogene ore zone. It is chalracteristically associated with the bornite-chalcopyrite pair, and is considered a minor ore constituent accounting for no greater than 2% of the hypogene ore.

In polished section, tetrahedrite-tennantite appears as a greyish white mineral with faint tinges of blue. Discrete isolated grains were not observed. Rather fine grained anhedral massas, blebs and lobate forms were always observed in a mutual boundary or replacement relationship with bornite-chalcopyrite, with a slight preference for chalcopyrite noted. In a number of specimens and under the highest magnification, microcrystalline inclusions of tetrahedrite-tennantite are observed 'peppered' throughout the host bornite-chalcopyrite. Textural relationships of tetrahedrite-tennantite are presented in Plate V - 1H, V - 2A, V - 2B.

(c) Pyrite

Pyrite is but rarely observed in the hypogene copper ore zone. It does however, form the dominant hypogene ore mineral in the zone previously referred to as the pyritic halo. The percentage of pyrite in this zone is somewhat variable, ranging from less than 1% up to 10% total volume.

Pyrite occurs as disseminated grains, veinlets, and veins. The average grain size of disseminated pyrite is in the order of 1.0 mm, though variations within wide limits are locally observed. The maximum width attained by

pyrite-bearing veins rarely exceeds 2.0 cm. Grain shape tends towards idiomorphic with well defined pyrite cubes being characteristic. In polished section, disseminated pyrite was frequently observed preferentially concentrated at former amphibole and pyroxene sites in propylitized and highly altered quartz-sericite rock. The occurrence of pyrite in this manner is thought to have resulted from sulfidization of the former iron-bearing minerals. Vein pyrite commonly displays a cataclastic texture in which larger grains have been fragmented and cemented along fractures and cleavage planes by a quartz-carbonate gangue (Plate V - 2C).

Locally, minor chalcopyrite is associated with pyrite in the peripheral halo. Where the two minerals are intergrown, chalcopyrite is sometimes observed replacing pyrite along irregular micro-fractures (Plate V - 2D). Pyrite is but rarely present in the hypogene copper zone. Pyrite here occurs mostly as isolated fine grained disseminations not displaying any obvious textural interrelationship with the copper sulfides.

(d) Marcasite

Marcasite is not a common mineral in the Afton deposit. It occurs in late stage veinlets and as a fine grained aggregate in vugs. A well developed colloform texture is exhibited by marcasite where it is present as open space fillings (Plate V - 2E). In veins, marcasite appears as an irregular granular aggregate with crystal outlines occasionally present. Chalcopyrite is observed in a replacement relationship with marcasite, with the former present as microscopic remnants and fine grained inclusions (Plate V - 2F). Replacement appears to have proceeded along grain boundaries. Marcasite is typically accompanied by quartz and carbonates, and less commonly by zeolites.

(e) Magnetite

Magnetite is widespread throughout the Afton deposit. It is present as disseminations, cross-cutting veins, and as small lensoid bodies. The veins differ markedly from the copper-bearing veins as they are often up to several centimeters wide and are more continuous over their length. Angular and subrounded fragments of highly altered Cherry Creek ? rocks are intermittently abundant in the veins, which often form smaller branching stockworks. The density of the veins and disseminations increase toward the eastern portion of the deposit, where the aforementioned magnetite zone is encountered.

Grain size varies from fine ($\leq$ 1.0 mm) to coarse ($\geq$ 5.0 mm) grained, with coarse grained magnetite generally restricted to veins. The grains display a decided tendency towards a euhedral habit, with lamellar twinning generally present. Commonly a cataclastic texture, similar to that displayed by the pyrite, is present. In some portions of the veins, brecciated magnetite fragments are enveloped and veined by later sulfides and gangue. The later sulfides include chalcopyrite and pyrite which are present as disseminations as well as cross-cutting veinlets.

Conspicuous white to light green apatite crystals are present intermittently within the majority of the magnetite veins. Under the microscope, apatite is seen as well formed euhedral crystals intergrown with magnetite (Plate V - 2C). Minor calcite, quartz, and siderite also accompany the magnetite veins as later cavity fillings and cross-cutting veinlets.

The association of magnetite and apatite with alkaline and calc-alkaline intrusions in orogenic belts has been noted elsewhere (Badham and Morton, 1976; Park, 1972). The magnetite-apatite-alkaline intrusion association observed at Afton and in the Iron Mask batholith may be explained by

Phillpotts (1967) hypothesis. Phillpotts (1967) proposed that a 2:1 magnetite:apatite mixture constitutes a eutectic mixture in the system magnetite-fluorapatite, and concluded that such a eutectic mix is immiscible with alkaline intermediate magma. Further, Phillpotts (1967) noted that magnetite-diorite-apatite mixtures, with apatite in excess of 30%, form three immiscible liquids on melting; an apatite-rich one; a magnetite-apatite melt; and a silicate melt. Such a process involving immiscibility of these phases may therefore have been responsible for the observed magnetite-apatite-diorite association of the Iron Mask batholith.

(f) Hematite

Specular hematite is present as veinlets and impregnations within the altered host rocks. Veinlets are narrow (1.0 cm), commonly brecciated, and consist of well developed idiomorphic crystals (Plate V-2H). Lamellar twinning is present in some grains, though others show no trace of twinning. Disseminated hematite occurs as needle-like crystals, acicular clusters, skeletal crystals, and fine grained allotriomorphic forms (Plate V-3A).

Specular hematite is often associated with magnetite. It occurs as separate grains in the neighborhood of magnetite and is observed in various stages of replacement with magnetite (Plate V-3B). Though some of the hematite may have formed independently, much of the specular hematite at Afton is thought to have formed from magnetite through martinization. Whether this has proceeded under hypogene or supergene conditions is however not fully substantiated by the available textural evidence. The cementative crusts of hematite around chalcopyrite-bornite are undoubtedly of secondary origin.

2. Supergene Minerals

The supergene minerals of the Afton deposit are defined as those

minerals which are thought to have been derived by the processes involving weathering, oxidation, and secondary enrichment. They are listed in Table V - 1 - A.

(a) Native Copper

Native copper is a prominent constituent of the Afton orebody, accounting for greater than 65% of the supergene ore. In this regard Afton is unique among the Canadian porphyry copper deposits as it is the only known deposit in which metallic copper is the major ore mineral. It is present in a variety of forms, is commonly associated with chalcocite, and generally displays a close spatial relationship to zones of oxidation.

The principal modes of native copper are as disseminations, blebs, thin seams, and veinlets. Favourable open space structures which have localized these forms include the following:

(i) Hairline and narrow fractures which vary from single widely spaced fractures to complex reticulate systems. The fractures are commonly coated and stained with limonite.

(ii) Fault breccia and crushed rock; these strongly deformed rocks are characterized by their highly friable nature and brick red color due to the presence of a ubiquitous hematitic limonite.

(iii) Pre-existing veins and veinlets; these include magnetite, and specular hematite.

(iv) Veinlets - calcite, epidote, and the associated gangue minerals, including chlorite with minor zeolite.

(v) Crackle breccia - highly altered and typically characterized by propylitic alteration.

The grain size of metallic copper is variable within wide limits, ranging from microcrystalline impregnations (< 10 μm) to coarse grained masses often exceeding 0.5 cm in diameter. Fracture fillings and veinlets of native copper are typically between 0.5 mm and 2.0 mm and rarely exceed 3.0 mm in width.

Under the microscope native copper exhibits a variety of habits. Allotriomorphic forms are most abundant (Plate V-3C, V-3D, V-3E). They consist of irregular shaped subrounded grains, 'porou' forms and spherulitic to dendritic growths. Less frequently metallic copper displays an idiomorphic to hypidiomorphic habit (Plate V-3F). Well defined crystals, some attaining 0.5 cm in length, are present in both veinlets and in fault breccias.

The association of native copper with chalcocite, as was discussed, defines the native copper-chalcocite ore zone. In this zone, metallic copper and chalcocite commonly do not display any textural interrelationships as they are mostly present as separate grains. However, where the two are intergrown, they either form a simple intergrowth or chalcocite is being replaced by native copper (Plate V-3G). Microscopic remnants of chalcocite within metallic copper were observed in the occasional specimen. A rare occurrence of a native copper-chalcocite microveinlet cross-cutting a chalcocite grain is presented in Plate V-3H.

Aside from these associations, native copper does not exhibit any textural relationships whatsoever to the other copper-bearing sulfides. In addition, no other copper-bearing minerals were observed in the supergene blanket zone that might represent an intermediate stage in the breakdown of chalcocite to native copper.

(b) Minor Secondary Copper Minerals

Locally, several minor secondary copper-bearing minerals are present in

the zone of oxidation associated with native copper. These minerals, which include malachite, azurite, chryscolla, cuprite, tenorite, and conichalcite, are generally restricted to the upper portions of the supergene zone where they are extimated to account for less than 5 wt.% of the supergene copper-bearing minerals. Rarely, trace amounts of malachite and azurite occur in the deeper portions of the supergene zone where they persist to depths of 300 m below the present surface.

(c) Chalcocite

Chalcocite is the second most abundant supergene ore mineral in the Afton deposit, accounting for between 10 to 30% of the supergene copper ore. Its presence with bornite in the upper portion of the hypogene zone, and its common association with metallic copper above this zone, defines an irregular chalcocite blanket. Within this blanket, chalcocite displays a similar mode to that of native copper, occurring as disseminations, blebs, veinlets, veins and replacement bodies. Most of the chalcocite observed by the writer is the 'steely chalcocite' variety, though lesser amounts of the 'sooty chalcocite' variety are also present. Grain size is typically fine ($\sim$1.0 mm), though more massive forms (>5 mm) are not uncommon. Veinlets are characteristically 1.0 to 2.0 mm wide with larger veins up to 2.5 cm rarely present. A typical occurrence of densely fracture controlled chalcocite mineralization is presented in Plate V - 4A.

Under the microscope, chalcocite appears as a bluish white homogenous mineral. It exhibits a variety of shapes, from highly irregular forms to well defined crystals. Idiomorphic chalcocite (Plate V - 4B), which displays pseudohexagonal crystal outlines, is restricted to vein and veinlet fillings. Calcite, quartz, epidote, chlorite, and less frequently barite are the associated gangue minerals.

The more typical allotriomorphic and hypidiomorphic chalcocite is present as impregnations and replacements in the altered host rocks, as well as occupying fractures and veinlets. The grains are most often subrounded to subangular with the occasional crystal outline present. A dendritic tendency is occasionally developed (Plate V - 4C) and porous and sponge-like forms are common. Veinlets of chalcocite are typically discontinuous, with chalcocite rarely occupying the veinlet over the entire length. Rather, chalcocite forms intermittant anhedral blebs, disseminations, and streaks with coarser grained masses present where a system of veinlets have coalesced. This feature is common in densely fractured rocks with the grains occupying the junctures of fracture and microfracture networks (Plate V - 4A).

Where chalcocite is associated with hypogene bornite and bornite-chalcopyrite intergrowths the mineral characteristically exhibits a replacement relationship to the earlier sulfides. The replacement structures are displayed in various stages from grain boundary rims and penetrations to masses in which the former sulfides are present only as relicts. Complete replacement/enrichment is inferred to have resulted in the disappearance of any traces of the initial ore throughout the greater part of the chalcocite blanket. Nowhere in the orebody was chalcocite observed replacing pyrite.

Chalcocite commonly makes its first appearance in the hypogene ore zone as discontinuous microscopic rims ($\sim$10 μm) enclosed within larger grains of bornite. The rims are generally of non-uniform width and possess rounded digitations which penetrate the host bornite. The bornite frequently contains minor chalcopyrite as an exsolution product (Plate V - 4D, V - 4E). As the chalcocite to bornite ratio increases (in a vertical sense), chalcocite

forms amoeboid-like blebs, irregular patches, lense-like bodies, together with very fine grained intragranular inclusions (Plate V - 4D, V - 4E, V - 4H). Monomineralic chalcocite also occurs as separate grains with the intergrowths. Where chalcocite becomes the dominant mineral species, relict textures of bornite in chalcocite are present. The bornite remnants generally appear as randomly dispersed forms throughout the chalcocite, which, in this association, commonly appears in porous and sponge-like forms (Plate V - 4F). Only rarely were bornite relicts restricted to the cores of the chalcocite grains. An unusual occurrence, observed only in one specimen, (Plate V - 4G), shows relict bornite surrounded by a uniform halo (15 μm) of blue digenite, contained in a larger chalcocite mass. Locally, chalcocite is superficially oxidized to cuprite and covellite.

The textural evidence alone does not fully substantiate either a hypogene or a supergene origin for the chalcocite at Afton. At Afton, unlike many other supergene enriched deposits in which chalcocite replaces pyrite, secondary chalcocite has replaced hypogene chalcopyrite and bornite, and hence is largely pseudomorphic after these minerals. Field and Gustafson (1976) report a similar situation at the El Salvador porphyry deposit in Chile. Such criteria as the complete disappearance of primary ore in the zone of enrichment, decrease of chalcocite and increase of bornite/chalcopyrite with depth, spatial relationship to fracture permeability and zone of oxidation, presence of the 'sooty' variety of chalcocite, and isotopic evidence, to be brought forth in Chapter VII, may all be cited as evidence for a supergene origin.

Some of the textures are, however, suggestive of primary processes (Plate V - 4G, V - 4H) and have been used as evidence for hypogene chalcocite in other deposits (Reed and Jambor, 1976), in which no apparent enrichment has

taken place. It is the writer's contention that though most of the chalcocite at Afton is of secondary origin, a quantitatively insignificant amount in the hypogene zone is of hydrothermal origin.

(d) Limonite

The presence of an extensive iron oxide cap, with irregular projections to depths in excess of 500 m, is indicative of a locally intense and deep reaching oxidation. The zone of oxidation, defined largely by the presence of limonite* together with insignificant copper oxides and carbonates, is coincident with and encloses a greater part of the enriched native copper blanket. Much of the red friable rock of the western half of the deposit, known for its spectacular native copper mineralization, is heavily stained and impregnated with brick red to reddish brown earthy hematite. Minor goethite together with lesser amounts of jarosite, are also present in the predominantly hematitic limonite.

Hematitic limonite is present as coatings on fractures, along veinlets, and as interstitial disseminations and impregnations within the host rocks. Locally, a rhythmically banded texture is displayed in vuggy intensely oxidized rock. No remnant boxwork or cellular type structures were observed in any of the limonitic zones. This supports Blanchard's (1968) observation that the porphyry copper deposits at best only yield a restricted amount of cellular pseudomorphs, and often none at all.

Preto (1972) and Carr and Reed (1976) have suggested that most of the limonite has been derived largely from the oxidation of magnetite. Such an interpretation is supported by both field and microscopic work as magnetite

* Limonite is used in a special sense in porphyry deposits to describe a mixture of amorphous ferric hydroxide, goethite, jarosite, lepidochrosite, hematite and other hydrous iron oxides.

can be observed altering in situ to a brick red indigenous limonite. Though magnetite does not break down readily, under special conditions such as strong fracturing, the presence of sulfides and a warm climate, (conditions which were present at Afton prior to the Middle Eocene), magnetite will readily oxidize.

Though some of the limonite at Afton has been drived from magnetite, other iron-bearing minerals (i.e. bornite, chalcopyrite, pyrite) may have contributed equally to its formation. That magnetite is solely the source for the limonite, which is in part transported and shows no evidence as to the nature of the parent mineral, is pure speculation.

The paragenesis of the ore minerals will be presented in the next chapter following a discussion of the associated hydrothermal alteration.

PLATE V - 1

PHOTOMICROGRAPHS OF ORE SPECIMENS

Afton Copper Deposit, B.C.

A. Sample D.D.H. 72 - 22 (- 75 m)

Microdiorite porphyry in which altered intermediate to low groundmass consists of an intricate mixture of interstitial chlorite (chl), calcite (cal), epidote (ep), and pyrite (py). Phenocrysts of plagioclase are mildly saussuritized. Sample is from propylitized pyritic halo. (Transmitted light, nicols X)

B. Sample D.D.H. 72 - 10 (- 389 m)

Intensely altered high groundmass diorite porphyry in which original rock forming minerals are represented by their alteration products. Note how pyrite (py) is preferentially concentrated at former ferromagnesian sites, which consist of an intimate mixture of biotite - chlorite - calcite - magnetite. (Transmitted light, nicols X)

C. Sample D.D.H. 72 - 22 (- 225 m)

Photomicrograph showing veinlet controlled hypogene chalcopyrite (cp) - bornite (bn) mineralization with lesser amount of disseminations. Note that the bornite - chalcopyrite intergrowths do not occupy the entire veinlet length. Associated gangue minerals (black areas) are biotite/chlorite and epidote. (Reflected plane light)

D. Sample D.D.H. 72 - 8 (- 298 m)

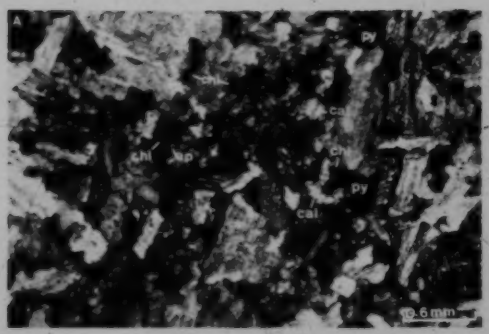
Fine grained hypogene bornite (bn) - chalcopyrite (cp) showing exsolution texture. Exsolution bodies of chalcopyrite appear as oriented lamellae, 'spindles', 'flames' and less regular bleb-like structures. Note also that simple intergrowths as well as isolated bornite and chalcopyrite disseminations are present. Alteration minerals (black areas) include secondary biotite, calcite, and epidote. (Reflected plane light)

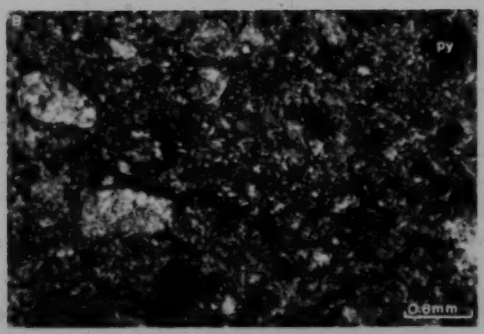
E. Sample D.D.H. 71 - 2 (- 235 m)

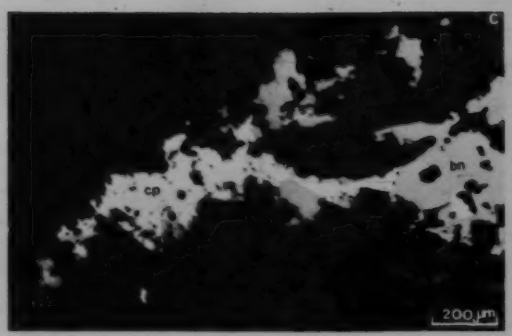
Coarse bleb of hypogene bornite (bn) with microscopic rim of chalcopyrite (cp) and sulfosalt phase (ss). The ore is transected by a late calcite veinlet (medium grey). Sample is from bornite zone in propylitically altered microdiorite porphyry. (Reflected plane light)

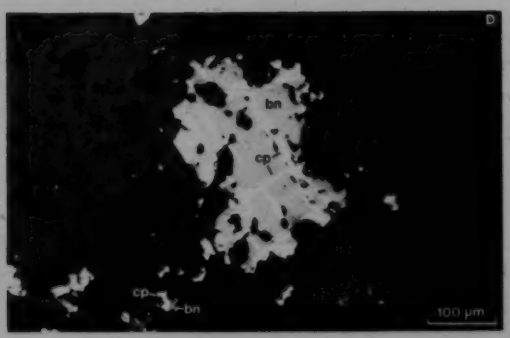
F. Sample D.D.H. 72 - 22 (- 283 m)

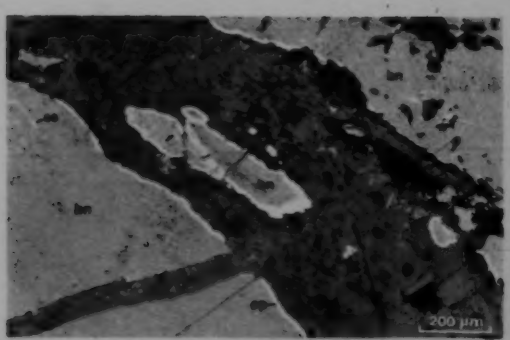
Fine grained subveinlet of hypogene bornite (bn) - chalcopyrite (cp) showing orientated chalcopyrite structures in host bornite. Host rock is intensely altered to a carbonate - clay mineralogy. Medium grey gangue around bornite - chalcopyrite is calcite. (Relfected plane light)

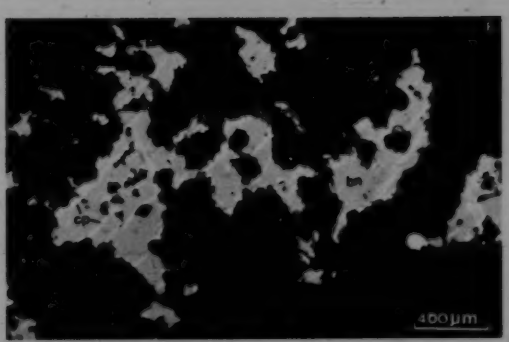

A
py
cp
chl
sp
py
cal
0.6 mm

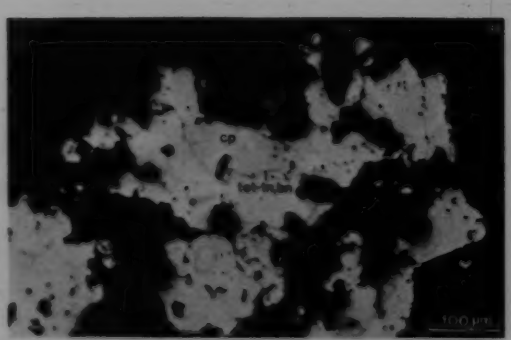

B
py
0.6mm


C
cp
bn
200 µm


D
bn
cp
cp
bn
100 µm


bn
200 µm


cp
400 µm


cp
100 µm

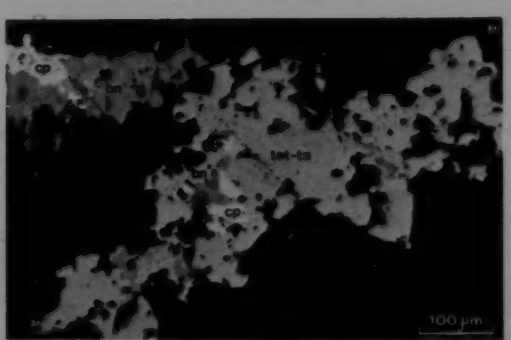

cp
bn
cp
100 µm

PLATE V - 1 (cont'd)

G. Sample D.D.H. 72 - 8 (- 297 m)

Allotriomorphic hypogene chalcopyrite (cp) grains with irregular microscopic 'seams' and 'atoll-like' structures composed of bornite (bn) - tetrahedrite-tennantite (tet-tn). (Reflected plane light, oil immersion)

H. Sample D.D.H. 73 - 32 (- 549 m)

Veinlet controlled hypogene chalcopyrite (cp) - bornite (bn) - tetrahedrite-tennantite (tet-tn) mineralization. Bornite appears to be replacing chalcopyrite (grain in upper left corner) as well as forming simple bornite-chalcopyrite intergrowths. Tetrahedrite-tennantite is replacing both chalcopyrite and bornite. Specimen is from deep level potassic alteration zone. (Reflected plane light)

PLATE V - 2

PHOTOMICROGRAPHS OF ORE SPECIMENS

Afton Copper Deposit, B.C.

A. Sample D.D.H. 73 - 32 (- 180 m)

Tetrahedrite-tennantite (tet-tn) is replaced by chalcopyrite (cp) both of which are partly brecciated. Sample is from late stage quartz - carbonate vein in the pyritic halo. (Reflected plane light)

B. Sample D.D.H. 72 - 8 (- 296 m)

Large chalcopyrite (cp) grain is replaced by tetrahedrite-tennantite (tet-tn), which is in turn transected by microveinlets of bornite (bn) and chalcopyrite. (Reflected plane light, oil immersion)

C. Sample D.D.H. 73 - 32 (- 93 m)

Hypogene cataclastic pyrite (py) in quartz - carbonate - sericite - gangue (white, light grey areas). Sample is from phyllic altered zone in the pyritic halo. (Transmitted light, open nicols)

D. Sample D.D.H. 72 - 10 (- 297 m)

Irregular and porous grains of hypogene chalcopyrite (cp) with euhedral pyrite (py). Microfractures in pyrite contain chalcopyrite. Mineralization is vein controlled with gangue consisting of quartz - calcite - dolomite. (Reflected plane light)

E. Sample D.D.H. 72 - 10 (- 381 m)

Late stage vug filling of fine grained colloform marcasite. Gangue consists of needle-like zeolite (black) in calcite (dark grey). Sample is from hypogene bornite - chalcopyrite ore zone. (Reflected plane light)

F. Sample D.D.H. 72 - 10 (- 318 m)

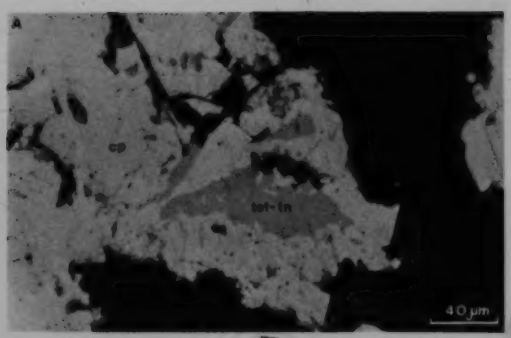
Veinlet controlled marcasite (mc) and chalcopyrite (cp) mineralization. The marcasite appears to have replaced a prexisting microveinlet of chalcopyrite. Note crystal outlines in upper portion of photo. Sample is from hypogene chalcopyrite - bornite zone. (Reflected light, oil immersion)

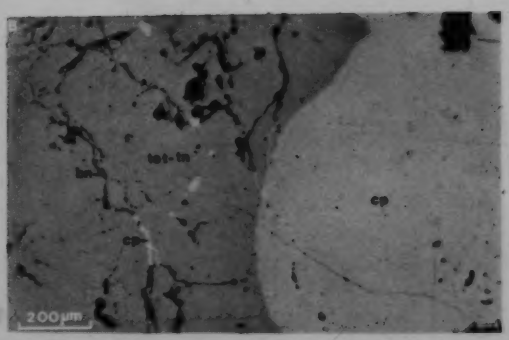
G. Sample D.D.H. 72 - 10 (- 371 m)

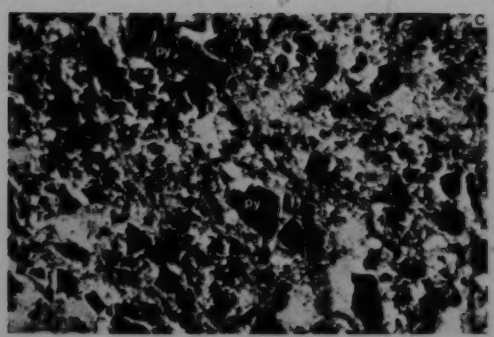
Vein of brecciated magnetite (mag) with euhedral apatite (ap) crystal. (Reflected plane light)

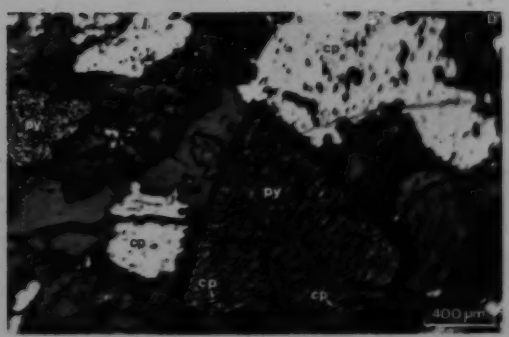
H. Sample D.D.H. 72 - 22 (- 386 m)

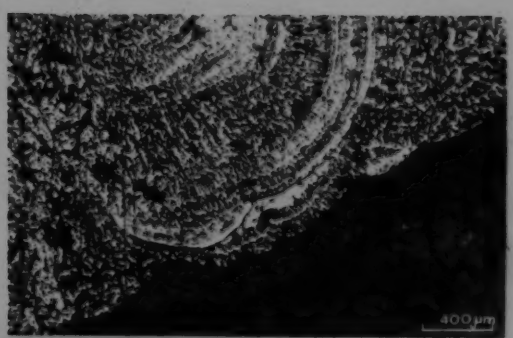
Veinlet of hematite (hm) cross-cut by microveinlet of epidote. Dark grey gangue betweeh brecciated hematite is epidote. Irregular blebs of native copper (Cu) occur intermittently along the epidote microveinlet. (Reflected plane light)

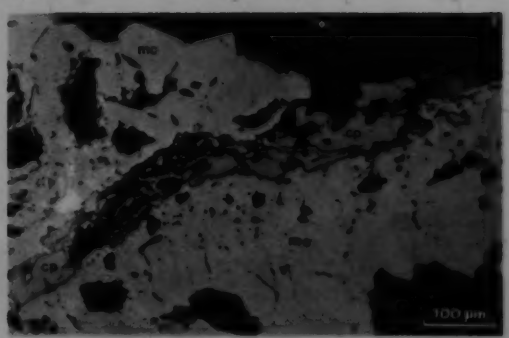

cp
tet-tn
40 µm


tet-tn
cp
cp
200 µm


C
py
py


B
cp
py
py
cp
cp
cp
400 µm


400 µm


mc
100 µm

ap

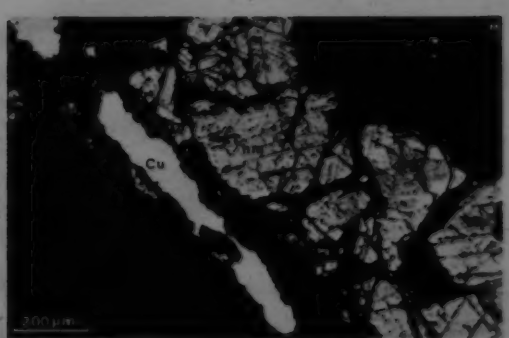

Cu
200 µm

PLATE V - 3

PHOTOMICROGRAPHS OF ORE SPECIMENS

Afton Copper Deposit, B.C.

A. Sample D.D.H. 72 - 10 (- 371 m)

Photomicrograph shows fine grained disseminated acicular hematite (hm). Grain in centre of photo consists of magnetite (mag) partly replaced by hematite. Larger grains near left and right photo margin consist of hematite which is pseudomorphic after magnetite. Medium grey gangue is calcite. (Reflected plane light)

B. Sample D.D.H. 72 - 8 (- 361 m)

Skeltal crystal of hematite (hm) with remnant of magnetite (mag). Sample is from telescoped propylitic - potassic alteration zone. (Reflected plane light)

C. Sample D.D.H. 72 - 7 (- 208 m)

Allotriomorphic fine grained native copper (Cu) occupying veinlet of calcite and epidote. (Reflected plane light)

D. Sample D.D.H. 71 - 2 (- 53 m)

Very fine grained disseminated native copper (Cu) preferentially concentrated in light grey calcite gangue. (Reflected plane light)

E. Sample D.D.H. 72 - 7 (- 203 m)

Typical irregular bleb of native copper (Cu) showing poorly defined crystal outlines. (Reflected plane light)

F. Sample D.D.H. 72 - 10 (- 30 m)

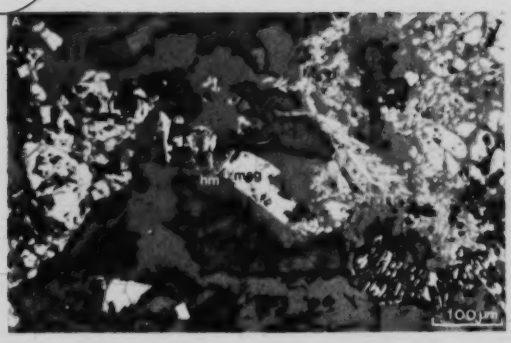
Photomicrograph shows fine grained native copper (Cu) - chalcocite (cc) crystals. Remnants of chalcocite are present within the native copper. Specimen is from supergene native copper - chalcocite zone. Gangue (black area) consists of chlorite, chalcedony and epidote. (Reflected plane light)

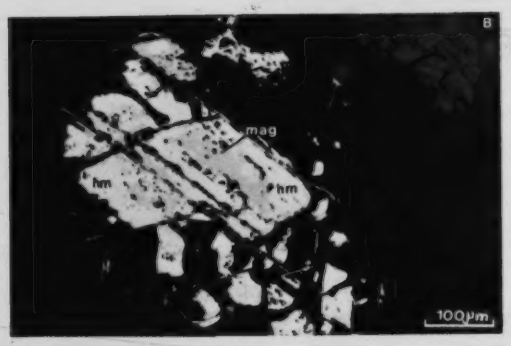
G. Sample D.D.H. 72 - 15 (- 36 m)

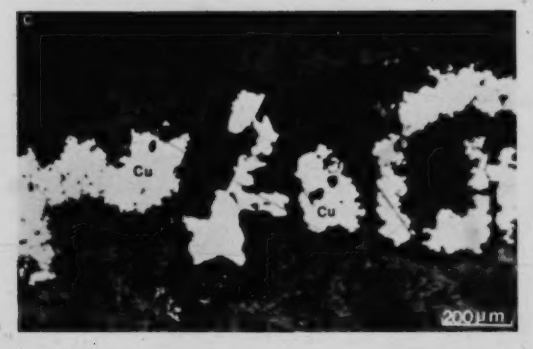
Fine grained native copper (Cu) - chalcocite (cc) mineralization with native copper replacing chalcocite. Note chalcocite fracture disease and microscopic chalcocite relicts in native copper. Sample is from highly fractured and oxidized portion of the supergene zone. (Reflected plane light)

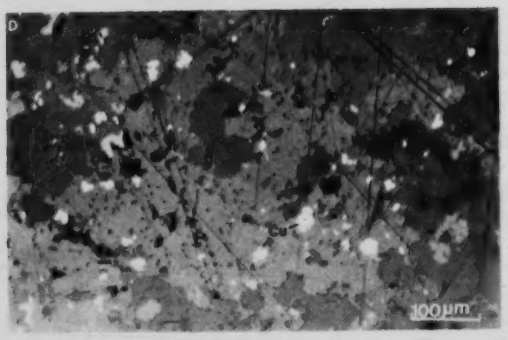
H. Sample D.D.H. 72 - 15 (- 36 m)

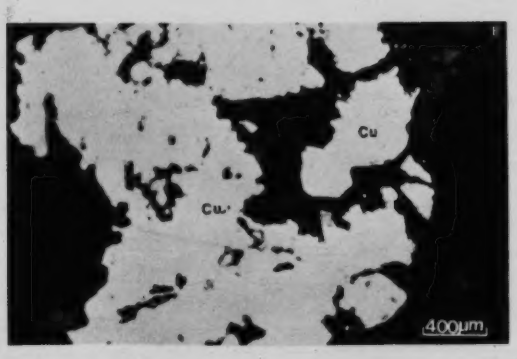
Fine grained disseminated and microveinlet controlled chalcocite (cc). The chalcocite grain in photo centre is cross-cut by a microveinlet containing native copper (Cu). Note tendancy of chalcocite towards euhedral habit at right centre of photo. (Reflected plane light)

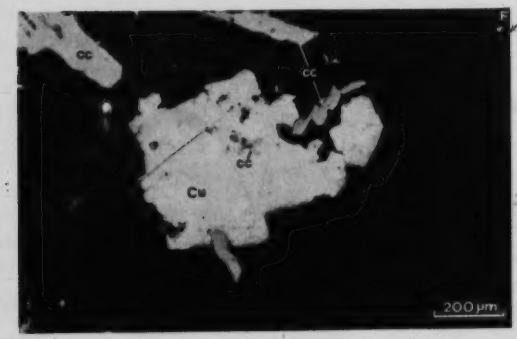

A
hm
mag
100µm

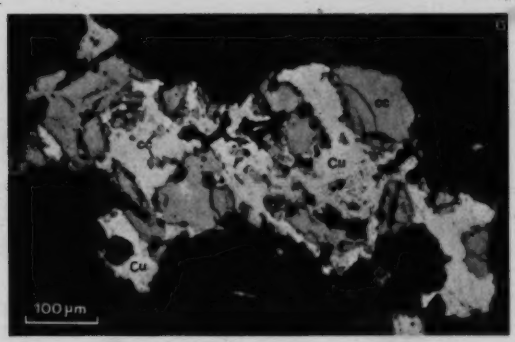

B
mag
hm
hm
100µm


C
Cu
Cu
200µm


D
100µm


Cu
Cu
400µm


cc
cc
cc
Cu
200µm


cc
Cu
Cu
100µm

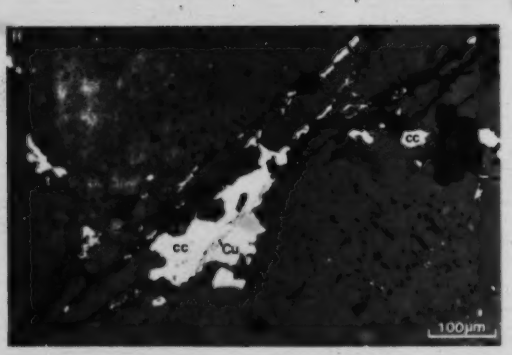

cc
cc
Cu
100µm

PLATE V - 4

PHOTOMICROGRAPHS OF ORE SPECIMENS

Afton Copper Deposit, B.C.

A. Sample D.D.H. 72 - 3 (- 88 m)

Intensely fractured intermediate groundmass diorite porphyry with high grade chalcocite (cc) mineralization. Host rock is dusted with iron-oxides which also coat fractures. Sample is from the supergene oxidation zone. (Transmitted light, open nicols)

B. Sample D.D.H. 72 - 10 (- 27 m)

Fine grained idiomorphic chalcocite (cc). The 'spine-like' feature in upper left corner is composed of microscopic chalcocite crystals. Dark grey gangue is quartz, chlorite and epidote. Specimen is from supergene native copper-chalcocite zone. (Reflected plane light)

C. Sample D.D.H. 72 - 3 (- 90 m)

Fine grained dendritic-like 'sooty' chalcocite. The finely dispersed (medium grey) grains are hematite. Specimen is from the supergene zone of oxidation. (Transmitted light, open nicols)

D. Sample D.D.H. 72 - 22 (- 282 m)

Hypogene bornite (bn) with chalcopyrite (cp) lamellae rimmed by very fine grained cementative chalcocite (cc). Chalcocite is replacing both bornite and chalcopyrite. Sample is from transitional bornite - chalcocite zone, some 45 m below the first appearance of native copper. (Reflected plane light)

E. Sample D.D.H. 72 - 22 (- 282 m)

Discontinuous chalcocite (cc) replacement rims around hypogene bornite (bn) - chalcopyrite (cp). Note tendancy of chalcocite towards crystal outline in lower margin of the bornite grain. (Reflected plane light)

F. Sample D.D.H. 73 - 32 (- 448 m)

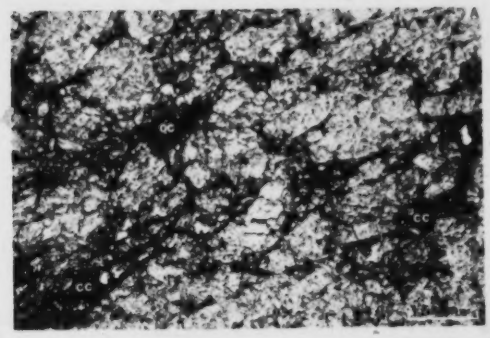
Fine grained allotriomorphic 'sponge-like' chlacocite (cc) with irregularily dispersed bornite (bn) remnants. Gangue (dark grey) consists of calcite, quartz, barite. (Reflected plane light)

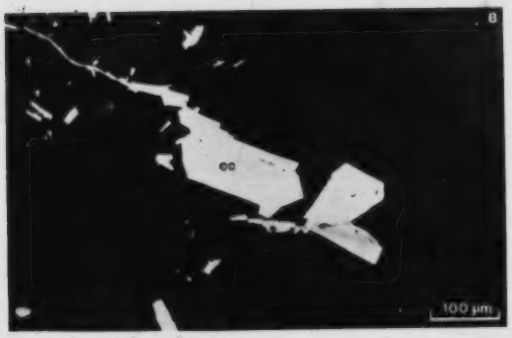
G. Sample D.D.H. 73 - 32 (- 373 m)

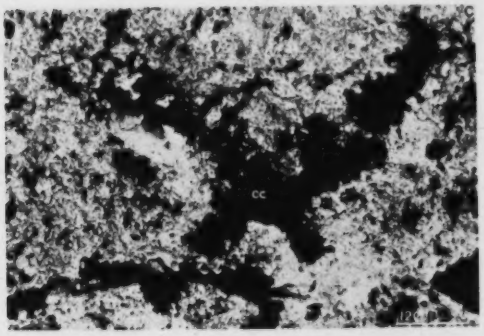
Fine grained irregular chalcocite (cc) mass containing bornite (bn) which is enclosed by a uniform halo of digenite (dg). (Reflected plane light, oil immersion)

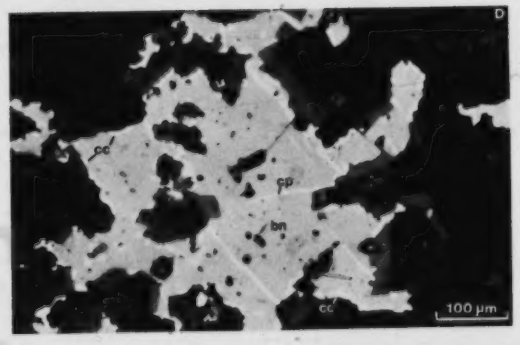
H. Sample D.D.H. 73 - 32 (- 400 m)

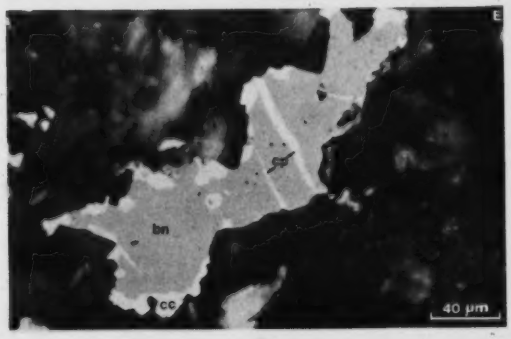
Hypogene bornite (bn) partly replaced by chalcocite (cc). The narrow discontinuous rim consists of hematite (hm) which is also present as microscopic intragranular replacement bodies. (Reflected plane light)

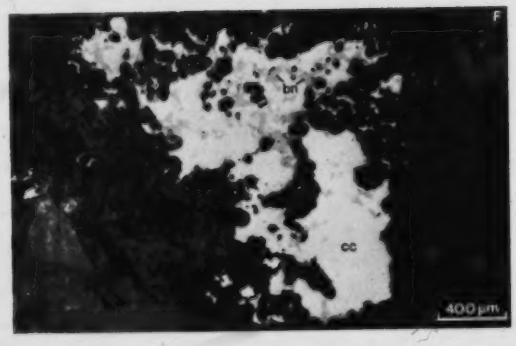

A
cc
cc
cc

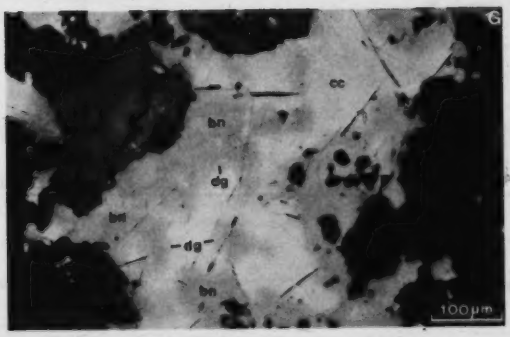

B
cc
100 µm

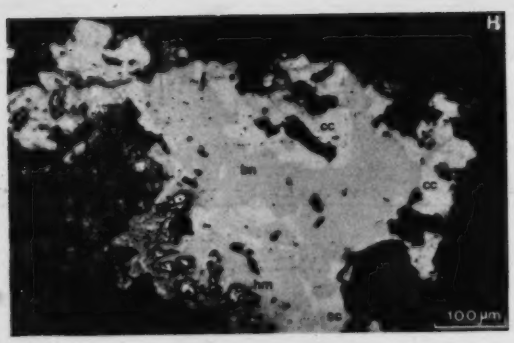

cc


D
cc
cp
bn
cc
100 µm


E
cp
bn
cc
40 µm


F
bn
cc
400 µm


G
cc
bn
dg
bn
dg
bn
100 µm


H
cc
bn
cc
bn
cc
100 µm

Chapter VI

HYDROTHERMAL ALTERATION

AND

PARAGENESIS OF ORES AND GANGUE

A. INTRODUCTION

Much has been written about hydrothermal alteration and the zonal patterns induced by it in the host and wallrocks of porphyry copper deposits. Since the early works by Creasy (1959) and Burnham (1962), who first attempted to systematize porphyry copper alteration in terms of a facies concept, the trend has been towards the establishment of uniform alteration models. Presently, the most generally accepted nomenclature for types of hydrothermal alteration in porphyry copper deposits is that followed by Lowell and Guilbert (1970). In their study of North American deposits, Lowell and Guilbert (1970) proposed a model for a 'typical' porphyry copper deposit in which the alteration is zoned from potassic at the core, outward through phyllic, argillic, and propylitic assemblages (Fig. VI - 1a). Since this model first appeared, many workers have employed it as a norm from which to compare other deposits. Recently, Godwin and Drummond (1976) adopted the Lowell and Guilbert (1970) model in an empirical evaluation of Western Canadian deposits.

The terms potassic, phyllic, argillic, and propylitic were derived by Lowell and Guilbert (1970) from earlier works (Burnham, 1962; Creasy, 1966; Meyer and Hemley, 1968; Lowell and Guilbert, 1967) to describe the four principal porphyry copper alteration assemblages. Each assemblage may be depicted on an AKF - ACF diagram (Fig. VI - 1b).

Potassic alteration is applied to assemblages consisting of introduced

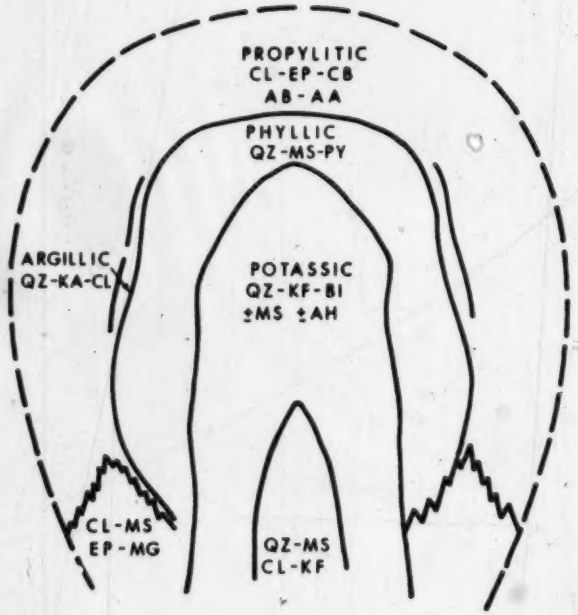


Fig. VI - 1a. Concentric alteration zoning in a typical porphyry copper deposit. (After Lowell and Guilbert, 1970)

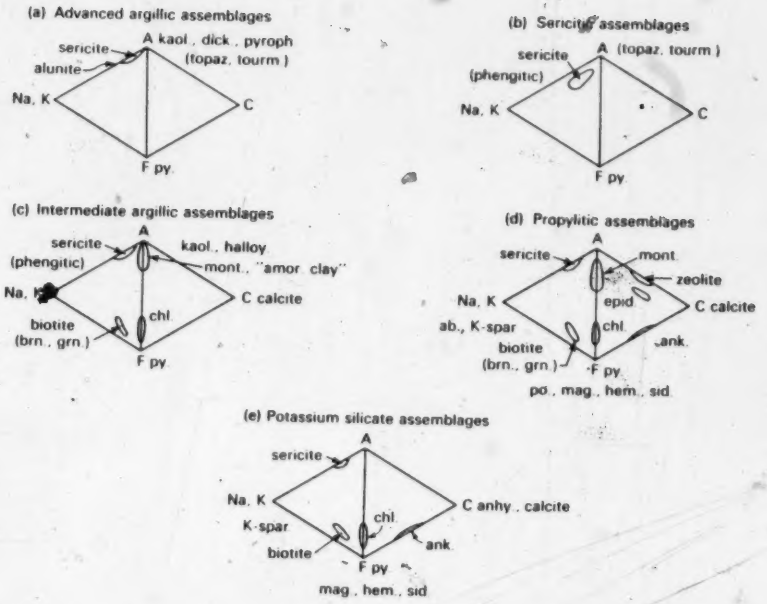


Fig. VI - 1b. AKF - ACF diagram depicting mineral assemblages in major types of wall rock alteration. (After Meyer and Hemley, 1967)

or recrystallized K-feldspar, quartz, and biotite, with minor sericite and anhydrite. Argillic and propylitic alteration is used to describe quartz-kaolin-montmorillonite-chlorite-biotite and chlorite-calcite-epidote-adularia-albite alteration assemblages, respectively. Phyllic alteration is applied to quartz-sericite-pyrite assemblages with less than 5% kaolin, biotite, or K-feldspar.

Though many deposits do fit the Lowell and Guilbert (1970) alteration-zonation model, it has become apparent, even to the original proponents (Lowell and Guilbert, 1974) that many do not. In particular, many of the Canadian porphyry copper deposits of calc-alkaline affinity depart from the norm (i.e. Bethlehem, Valley Copper, J.A. orebody). In addition, with the discovery of several new Canadian deposits, it is now recognized (Barr et al., 1976) that the alkaline suite of porphyries as a class (of which Afton is included), also do not adhere to the classic zoning pattern evident in the Lowell and Guilbert (1970) model.

In this section the various alteration assemblages* and zonation pattern, as it is presently known at the Afton deposit, will be considered. Paragenesis of the ore minerals and alteration assemblages will be considered at the end of this chapter.

B. GENERAL FEATURES AND ALTERATION ZONATION

At Afton, the writer has recognized mineral assemblages which can be assigned to propylitic, potassic and phyllic alteration types. The various assemblages are listed in Table VI - 1. An age of 198 ± 6 m.y. obtained from

* Alteration assemblages in this study (and as adopted from its general usages elsewhere (Meyer and Hemley, 1967) refers to specific, usually characteristic, and repeatedly observed mineral associations. Stable equilibrium is not necessarily implied.

K-Ar determinations on hydrothermal biotite (Preto, pers. comm.) from an adjacent property to Afton implies that intrusion of the Cherry Creek suite, and hydrothermal alteration were closely related in time. Further, nowhere in the deposit were the hypogene sulfides and oxides not spatially coextensive with hydrothermal alteration, though locally, alteration is not accompanied by copper mineralization.

Intensity of alteration is highly variable over short distances. No gradual progression in terms of alteration intensity exists within or between the alteration zones. Alteration within any given ore zone characteristically involves both pervasive and veinlet replacement of the primary rock-forming minerals. This process is so complete that in some portions of the orebody, none of the original rock components are discernable.

The outer limits of hydrothermal alteration are as of yet imperfectly known, and warrant further investigation. Alteration effects can be recognized at least in distances of 700 m from the main orebody. Transition from altered rocks downward to relatively fresh ones was noted only in the deepest drill penetrations of the footwall.

A well defined alteration zonation pattern is not megascopically evident within or around the Afton orebody, though a poorly defined zonation exists. The lack of a broad, well defined concentric zonation with regard to alteration appears to be a function of several variables. The smaller porphyry copper deposits ($< 75 \times 10^6$ metric tons) such as Afton, as well as other deposits of similar size and nature (in terms of age, host, mineralization, alteration) in British Columbia (i.e. Ingerbelle, Copper Mountain, Lorraine) typically do not display the zoning pattern evident in many of the larger deposits and illustrated (Fig. VI - 1a) in the Lowell and Guilbert (1970) model. Distribution of alteration minerals, aside from the fundamental

physical and chemical controls (i.e. temperature, pressure, Eh, pH, H^+ activities, f_{O_2} etc.) has been strongly influenced by structural controls such as faults, fractures, and breccia zones. Structural anisotropism, steep physical and chemical gradients are common features of the shallow volcanic subvolcanic environment under which alteration and mineralization occurred at Afton. Complex telescoping and overlapping of alteration assemblages, as well as short range variations in alteration intensity, should therefore be expected. The environment of ore deposition will be discussed more fully in Chapter VII.

Another important factor influencing the style of alteration at Afton is the composition of the pre-ore wall rocks. Alkaline intrusive rocks (see alkalis v.s. silica plot for unaltered Iron Mask rocks, page 112) in contrast to intermediate calc-alkaline intrusions, are undersaturated with respect to silica, and are relatively rich in iron and magnesium, with moderate amounts of calcium. Hydrothermal fluids invading such an environment under the appropriate conditions would certainly influence the system towards the formation of more mafic alteration minerals. The presence of potassium and high activities of iron and magnesium, as would be expected in such an environment, should expand the stability fields of biotite and K-feldspar and promote the development of other secondary iron-bearing silicates such as epidote and chlorite. Resultant widespread propylitic and biotite potassic zones should not be considered atypical manifestations of hydrothermal alteration in lieu of the pre-ore host rock composition. Both experimental and theoretical considerations (Meyer and Hemley, 1967; Hemley and Jones, 1964; Lowell and Guilbert, 1974) as well as the recurrence of similar alteration assemblages in other deposits of alkaline affinity (i.e. Cariboo Bell, Copper Mountain/ Ingerbelle, Galore Creek) support such an

observation.

C. POTASSIC ALTERATION

Several workers have used a variety of methods to describe potassic alteration. Fluid inclusions (Roedder, 1971), stable isotopes (Sheppard et al., 1971), mass transfer calculations (Helgeson, 1970) as well as a host of other chemical and thermodynamic techniques (Hemley and Jones, 1964; Beane, 1974) have been employed. Creasey (1966) depicted the potassic alteration environment as one with high K content and perhaps even addition of K. Most workers agree that the essential minerals that distinguish this alteration type are secondary potassium feldspar and micas (biotite and/or sericite). A variety of other minerals, including quartz, apatite, anhydrite, chlorite, iron-bearing carbonates, calcite, hematite and magnetite may be present.

At Afton, zones of potassic alteration were delineated by the writer in several portions of the orebody. In general, zones of potassic alteration were encountered in the deeper penetrations of the deposit, and were typically superimposed by an outer more widespread propylitic alteration. Though this progression in alteration from deeper potassium-silicate alteration upward and outwards into propylitic alteration is evident in a number of sections, it should by no means be considered a characteristic feature throughout.

Potassic alteration at Afton involves both the pervasive and veinlet to subveinlet replacement of primary minerals by essential biotite and K-feldspar. In hand specimen, rocks with advanced potassic alteration are typically a light grey to pinkish color, in contrast to the green pigmentation of propylitized rocks. Other minerals identified in the zones of potassic alteration include lesser amounts of apatite, carbonate, chlorite, sericite, magnetite,

hematite and epidote.

Secondary K-feldspar at Afton consists of orthoclase with lesser microperthitic orthoclase. These minerals replace the igneous groundmass of the porphyries, replace rim and vein original feldspar phenocrysts to varying degrees, or are otherwise present in veinlets (Plate VI - 1A to VI - 1G). Locally the replacement has been so complete that the original rock consists almost entirely of secondary K-feldspar.

In contrast to the primary rock-forming minerals, secondary K-feldspar often attains considerable dimensions, with diameters in excess of 2.0 cm present. In hand specimen, a distinctive pink to orange pigmentation is often displayed by secondary K-feldspar. This feature, upon microscopic examination, was seen to be due to the presence of microcrystalline inclusions of red hematite (Plate VI - 1D). Meyer and Hemley (1967) have suggested that the association of hematite in this manner with secondary K-feldspar of other occurrences, is the result of exsolution of Fe^{3+} from aluminum sites as hematite.

Secondary biotite (Plate VI - 1C, VI - 1G, VI - 1H) is a common associate of secondary K-feldspar, though it is not entirely restricted to these zones. Also, intense feldspathization is present without accompanying biotite. Pervasive and subveinlet biotization of porphyry groundmass to varying degrees, 'seive-like' pseudomorphic replacements of ferromagnesian minerals, and minor pervasive and twin controlled replacements of plagioclase phenocrysts are the principal modes of secondary biotite.

Secondary biotite at Afton is distinguished by its light brown to light green color, lower birefrigence than primary rock biotite, and generally fine 'scaley' subhedral to anhedral form. These features appear to be common to secondary biotite described from other deposits (Nielsen, 1968; Lowell and

Guilbert, 1970; Carson and Jambor, 1976). Locally secondary biotite is present in amounts up to 50 wt.%. Unlike primary rock biotite, grain dimensions of secondary biotite rarely exceed 0.2 mm. Biotite clusters, some of which display pseudohexagonal outlines, were commonly noted at former ferromagnesian sites. Minor cleavage controlled intergrowths of chlorite with biotite as well as fine grained iron oxide inclusions are present.

Apatite is a minor but characteristic accessory mineral in the potassic zone, and is widespread throughout most of the other altered rocks. It occurs both as a veinlet constituent and as pervasively distributed crystals, commonly associated with biotite (Plate VI - 2A). Apatite-bearing magnetite veinlets were discussed in Chapter IV. Minor sphene, calcite, and epidote are often present in zones of potassic alteration, with the latter two minerals representing the telescoping effect of a younger propylitic alteration (Plate VI - 1F).

The breakdown of plagioclase to sericite and/or clay, as well as saussuritization of plagioclase is a characteristic feature of alteration throughout the Afton deposit. Rarely did a sample not contain unaltered plagioclase. Within zones of potassic alteration, plagioclase is unstable, and is typically altered to a fine grained sericite. In some specimens, plagioclase cores were more highly altered than rims, probably reflecting an original compositional zonation. Unaltered albitic plagioclase is present locally within zones of potassic alteration (Plate VI - 1E). The development of sericite, however, may not be entirely contemporaneous with secondary K-feldspar/biotite alteration and is certainly not coextensive. Veinlets and microveinlets of sericite, with or without sulfides, were observed cross-cutting secondary K-feldspar (Plate VI - 1D).

Noteworthy at Afton is the absence of anhydrite from the potassic zone. Lowell and Guilbert (1970) consider anhydrite to be a minor but characteristic mineral in their potassic assemblage, and others (Meyer and Hemley, 1967) have observed that it is a frequent constituent of potassic alteration. The apparent lack of anhydrite at Afton could be due to: (1) low sulfate solutions, as has been suggested by Barnes (1965) to explain the scarcity of anhydrite and barite* in other hydrothermal systems; (2) and/or anhydrite in contact with groundwater, as has been suggested by Meyer and Hemley (1967), commonly undergoes hydration and resolution with the resultant gypsum removed often at considerable depth (i.e. several thousand feet). Both conditions may have been present at Afton thought gypsum, if present at all, was probably of supergene** origin as deep level assemblages (not showing any apparent supergene effects) lack anhydrite.

D. PROPYLITIC ALTERATION

Although there is not complete agreement in defining the term propylitic alteration, nor in specifying which minerals are essential, most workers agree this type of alteration is distinguished by the prominence of calcium-bearing minerals such as calcite and epidote, usually accompanied by chlorite. Burnham (1962) proposed that epidote is essential, though Creasey (1966) argues that in some assemblages a carbonate is the stable calcian mineral rather than a member of the epidote group.

* Barite and gypsum were only noted in late stage veinlets at the Afton deposit.

** The generation of supergene gypsum and other complex sulfates is a well known phenomenon in the oxidation of sulfide orebodies. Its rarity at Afton may be explained by groundwater solution.

Creasey (1966) proposed the four following assemblages on the basis of observational and ACF compatibility diagrams: (1) chlorite-calcite-kaolinite; (2) chlorite-calcite-talc; (3) chlorite-epidote-calcite; and (4) chlorite-epidote. SiO_2 and H_2O occur in excess and quartz is always a phase in the final assemblage. The first three assemblages form in the presence of considerable CO_2, whereas chlorite-epidote is a low CO_2 assemblage. The addition of K_2O and Na_2O as components in this system would give rise to muscovite (sericite) and albite. Creasey (1966) also reports that sphene, leucoxene, and apatite are stable mineral phases. Hemley and Meyer (1967), using a similar approach (ACF-AKF diagrams), proposed that propylitic assemblages include epidote (zoisite, clinozoisite), albite, chlorite, septachlorite, carbonate; commonly with sericite, pyrite and iron oxides, and less commonly with zeolites or montmorillonite. The ACF-AKF compatibility diagram for propylitic alteration assemblage is shown on Figure VI-1b.

In contrast to the incipient and peripheral nature of propylitic alteration observed in many deposits of calcalkaline affinity in the S.W. United States and Canada (i.e. Santa Rita, New Mexico; San Manuel, Arizona; Lornex, British Columbia; Krain, British Columbia) and presented in the Lowell and Guilbert (1970) model, propylitic alteration at Afton is ubiquitous, widespread, and present throughout the ore zone.

The prominence of epidote, chlorite, and calcite in the altered rocks at Afton was used to delineate zonal boundaries between potassic and propylitic alteration. However, due to the presence of variable amounts of biotite and K-feldspar in propylitized rocks, zonal boundaries were rarely sharply delineated. Other minerals include apatite, iron oxides, albite

sericite, kaolin, montmorillonite*, talc, prophyllite*, sphene, zoisite, and less commonly prehnite, zeolite, quartz, barite, dolomite, ankerite, gypsum, and chalcedony.

Epidote should perhaps be considered diagnostic of propylitic alteration at Afton. It is commonly present in veinlets as well as being pervasively distributed throughout the prophyry groundmass (Plate VI-2B). Varying degrees of feldspar destructive alteration of plagioclase by epidote and conversion to a very fine felted mixture of carbonate, chlorite, and clay/sericite alteration was observed throughout zones of propylitic alteration (Plate VI-1C, VI-2D). Portions of the original zoned plagioclase are often 'homogenized' to what is thought to be predominantly white albite or sodic oligoclase, though the composition in many instances was indeterminable.

Unaltered primary rock-forming ferromagnesian minerals are all but lacking in propylitized rocks. Chloritization, often accompanied by calcite and epidote, is characteristic. In the most advanced stages of propylitic alteration primary ferromagnesian minerals are represented only by their alteration products.

Secondary biotite with and without secondary K-feldspar was observed in a number of propylitic assemblages commonly associated with epidote. Within these assemblages biotite displays varying degrees of stability from fresh through insipient chloritization to almost completely chloritized. Secondary biotite is also replaced by rare lensoid prehnite which in turn is partly pseudomorphed by epidote (Plate VI-2E). Biotite also appears to be more

* The presence of pyrophyllite, kaolinite, and montmorillonite was confirmed by x-ray diffraction studies (Preto, 1972; Lakefield Research).

central to the main copper ore zone as it is almost never observed in the peripheral pyrite-magnetite zones. Local conditions, such as the activity of K^+, may have been a determining factor in the stability or metastability of biotite during propylitic alteration. The writer is unaware of any experimental work on conditions for biotite-chlorite stability.

Chlorite, in addition to replacing hornblende (Plate VI - 2F), plagioclase, and secondary biotite, also occurs as replacements of porphyry groundmass and as a veinlet component (Plate VI - 2G). Less frequently, chlorite was observed replacing epidote. Minor zoisite is associated with chlorite.

The available geological evidence does not concur with Carr and Reed's (1976) observation that calcite is not a normal product of propylitic alteration at Afton. On the contrary, calcite (carbonate) is considered by the writer to be a normal product of propylitic alteration at Afton. It occurs abundantly in veinlets, as an alteration product after plagioclase, is present as vug fillings, and locally forms envelopes to epidote veinlets (Plate VI - 2B). Chlorite, showing well developed rosette and bow-tie textures is a normal component in calcite veinlets (Plate VI - 2H) and less commonly zeolite, quartz, albite, dolomite, and ankerite may be present (Plate VI - 3A, VI - 3B, VI - 3C, VI - 3D). Barite (Plate VI - 3B) and gypsum were only observed in late stage veinlets and quartz is more common in peripheral veinlets. Zeolite was tentatively identified as natrolite (Dr. R.D. Morton, per. comm.) but a rarely observed pink zeolite is thought to be heulandite.

Many of the calcite veinlets at Afton are post-ore in age as they in-

variably cross-cut all Cherry Creek rock types, as well as hypogene and supergene mineralization. The various stages of calcite veining observed at Afton will be considered under paragenesis.

Apatite is a characteristic but minor component of propylitic alteration. It occurs as fine disseminations and as a veinlet constituent. Some of the apatite probably represents original recrystallized rock-forming apatite, though hydrothermal introduction and redistribution has resulted in local concentrations up to 6 wt.% of this mineral. Minor fine grained sphene and ilmenite are also present intermittently throughout the propylitized rocks at Afton. Sphene is locally associated with carbonate.

E. PHYLLIC ALTERATION

Phyllic alteration, consisting of fine grained quartz and sericite, with or without chlorite and carbonate is present at Afton. This alteration type, which was recognized earlier by Preto (1972) has affected a much smaller volume of rock that propylitic alteration and is generally peripheral to the main copper orebody. Phyllic alteration grades into zones of propylitic alteration, which typically enclose it. Together these two alteration types encompass the pyrite 'halo' and affect both Nicola volcanics and Cherry Creek porphyry.

Phyllic alteration is usually so advanced that original rock components and texture are no longer discernable. Both pervasive and vein replacements are present (Plate VI - 3E, VI - 3F, VI - 3G).

F. PARAGENESIS OF ORES AND GANGUE

The relative ages of alteration and mineralization at Afton have been

determined from cross-cutting relationships, polished and thin section exsolution and replacement features, and veinlet zoning. The available evidence indicates that alteration and metallization were spatially contemporaneous and coextensive. The known paragenetic sequence of opaques and gangues is illustrated in Tables VI - 1 and VI - 2. A brief outline follows.

Sequential and overlapping stages of deposition of hypogene copper-bearing minerals and iron oxides occurred throughout the potassic and propylitic stages of alteration. Five main rock alteration assemblages are recognized. The apparent bornite-chalcopyrite zonation, as discussed in Chapter IV, does not conform to any known alteration zonation within the hypogene copper ore zone. Pyrite, with minor chalcopyrite, formed during the propylitic and phyllic alteration. The relative age of the principal and minor copper-bearing minerals and accompanying oxides are shown in Figure VI - 2.

As illustrated in Table VI - 1, considerable overlap of alteration/mineralization is present within the Afton deposit. However, on the basis of the effects on the least altered rocks, cross-cutting relationships of propylitic stage veinlets (see Plate VI - 1H) and the apparent instability of biotite with advanced propylitization, it is thought that potassic alteration was earlier than the propylitic stage.

Introduction of secondary K-feldspar and formation of hydrothermal biotite appear to be the earliest expressions of hydrothermal alteration. Secondary K-feldspar may be genetically related to the late intrusion of potassic Cherry Creek igneous phases, though a spatial relationship, grading from zones with secondary K-feldspar into primary monzonite and syenite, is not evident. Deposition of bornite and chalcopyrite, with lesser amounts of tetrahedrite-tennantite is coincident with the secondary biotite stage. This stage was

TABLE VI - 1

Paragenesis of Alteration/Mineralization

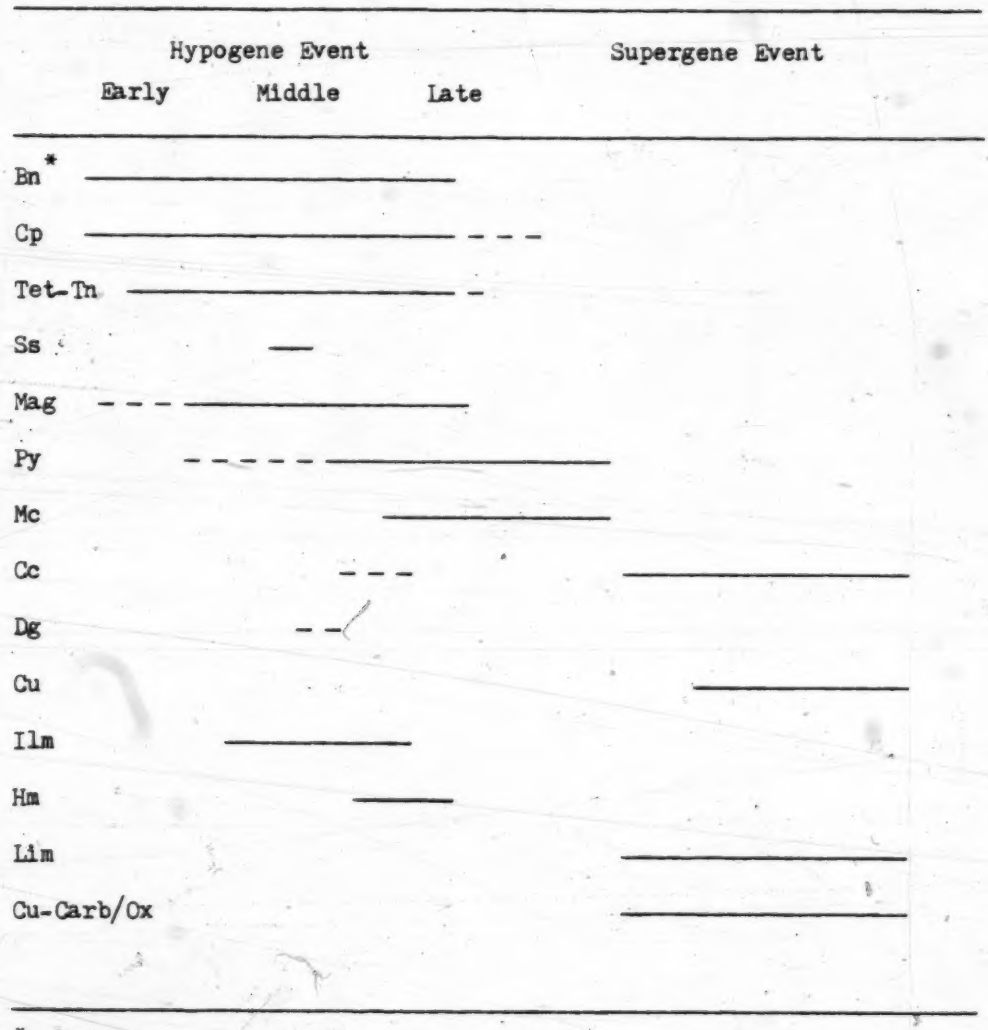
Afton Copper Deposit, B.C.

Relative Age	Alteration*	Stage No.	Alteration/Ore Assemblage**
Early Hypogene	Potassic	Stage 1	K-Fsp ± Bi ± Ser ± Hm ± Bn ± Cp ± Mag
		Stage 2	Bi + Ep + Chl + Cal + Ab ± Ap ± Mag ± Spn ± Q ± Ser ± Clay ± Prn ± Bn ± Cp ± Mag
	Propylitic	Stage 3	a) Ep + Chl + Cal ± Ab ± Ap ± Spn ± Zo ± Tc ± K-Fsp ± Prn ± Ser ± Clay ± Bn ± Cp ± Mag
Middle Hypogene			b) Cal + Chl ± Ab ± Q ± Ser ± Clay ± Bn ± Cp ± Mag
	Propylitic Magnetite Vein Period	Stage 4 Veins/ Veinlets	Ep + Chl + Mt + Ap + Cal ± Sid ± Hm ± Ill ± Ank
Late (Peripheral) Hypogene	Phyllic and/or Propylitic	Stage 5	a) Cal + Chl ± Q ± Ser ± Ep ± Py ± Cp
			b) Q + Ser + Py ± Cal ± Chl ± Mag ± Cp
			c) Q + Cal + Py ± Cp
			d) Cal + Chl ± Dol ± Zeo ± Sid ± Gyp ± Bar ± Py ± Mc
			e) Chl + K-Fsp + Py
Post-Ore Pre-Supergene		Stage 6 Veins/ Veinlets	Q + Carb
Supergene	Oxidation Argillic?	Stage 7	Hm ± Gth ± Jar ± Clay ± Cu ± Cc ± Cu-carb/ox
Post-Supergene		Stage 8 Veins/ Veinlets	Cal + Q

* Alteration includes both pervasive and vein type unless otherwise indicated.
** For key to abbreviations see Appendix VI.

Figure VI - 2

Paragenesis of Ores, Afton Copper Deposit, B.C.



* For key to abbreviations see Appendix VI.
—— Indicates major period of deposition.
– – Indicates minor period of deposition.

closely followed, and probably coincident in some portions of the deposit, with the propylitic stage. Bornite and chalcopyrite mineralization accompanied by chloritization, epidotization, and calcitization, continued throughout the propylitic stage. A major episode of magnetite-apatite veining, with lesser hematite, occurred during the propylitic stage and culminated in the formation of the magnetite zone in the extreme eastern portion of the deposit. Magnetite veining occurred prior to stage 5 pyrite-chalcopyrite mineralization, as the magnetite veins are invariably transected by and in part replaced by these two minerals.

Pyrite-quartz-sericite phyllic stage alteration and pyrite-propylitic alteration are partly coincident and in part later than the main hypogene copper propylitic stage. Advanced phyllic alteration has obliterated the effects of propylitic alteration, into which it is gradational, and is therefore thought to be younger. The vein-veinlet assemblage, quartz + calcite $\pm$ pyrite $\pm$ chalcopyrite represents one of the final metallization/alteration events at Afton. Also considered to be one of the final stages of hypogene metallization and alteration at Afton is the development of veinlets and vug fillings of carbonate and zeolite. Many are post-mineral in age, though iron sulfide (marcasite-pyrite) is locally a constituent.

Several generations of post-hypogene barren calcite vein-veinlets cross-cut the ore zone. Some are pre-supergene, as they are invariably transected by native copper, while others are of a younger post-supergene age.

Supergene alteration and mineralization at Afton can be tentatively assigned a pre-Tertiary age on the basis of unaltered and unmineralized

Tertiary volcanic dyke rock which cross-cuts the supergene zone (Carr and Reed, 1976). Where evident, native copper deposition typically follows that of chalcocite. Development of copper oxides and carbonates, as well as hematitic limonite, probably occurred throughout the supergene event, though the paragenetic relationship among these minerals is never apparent. Some of the surficial copper carbonates and oxides may have formed since the deposit was exposed subsequent to Pleistocene glaciation.

PLATE VI - 1

PHOTOMICROGRAPHS OF ALTERED CHERRY CREEK ROCKS

Afton Copper Deposit, B.C.

A. Sample D.D.H. 72 - 10 (- 371 m)

Photomicrograph shows secondary K-feldspar replacing Cherry Creek porphyry. Large plagioclase phenocryst, which is rimmed and inundated by secondary K-feldspar, is altered to fine grained sericite. Secondary K-feldspar is dark due to the presence of abundant hematite. (Transmitted light, nicols X)

B. Sample D.D.H. 72 - 22 (- 305 m)

Characteristic secondary biotite (bi) and K-feldspar (K-fsp) alteration with accompanying bornite (bn) - chalcopyrite (cp). Note fine grained 'scaly' nature of biotite, which is partly altered to chlorite. (Transmitted light, nicols X)

C. Sample D.D.H. 72 - 22 (- 333 m)

Secondary K-feldspar (K-fsp) and fine grained secondary biotite (bi). Dark grey areas are chlorite with lesser amounts of sphene. Note plagioclase (plag) in K-feldspar at photo centre. (Transmitted light, nicols X)

D. Sample D.D.H. 73 - 32 (- 543 m)

Photomicrograph shows specimen from deep potassic alteration zone. Phenocrysts and fine grained groundmass consist almost entirely of secondary K-feldspar (K-fsp). Microcrystalline inclusions of hematite are present in the phenocryst in lower right hand corner. Sericite (ser) veinlet with bornite (bn) - chalcopyrite (cp) transects the zone. (Transmitted light, nicols X)

E. Sample D.D.H. 72 - 17 (- 177 m)

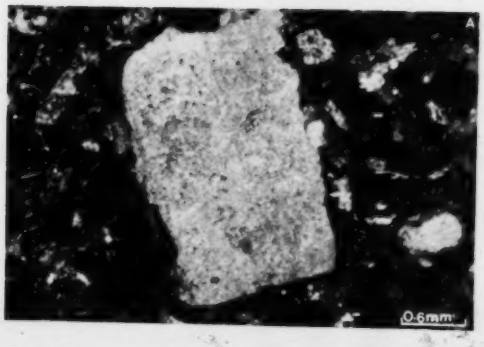
Photomicrograph shows pervasive potassic alteration. Albitic plagioclase, in photo centre, is stable. Carbonate-chlorite-alkali microveinlets cross-cut the zone. (Transmitted light, nicols X)

F. Sample D.D.H. 72 - 8 (- 361 m)

Photomicrograph illustrates overlap of propylitic and potassic alteration. Zone of secondary K-feldspar (K-fsp) is cross-cut by epidote (ep) veinlet, both of which are transected by microveinlets of calcite (cal). (Transmitted light, nicols X)

G. Sample D.D.H. 72 - 8 (- 298 m)

Photomicrograph shows biotite (bi) - K-feldspar (K-fsp) envelopes around hypogene bornite (bn) - chalcopyrite (cp). Relict amphibole (amph) is partly biotized and plagioclase (pl) is converted to fine felted sericite. (Transmitted light, nicols X)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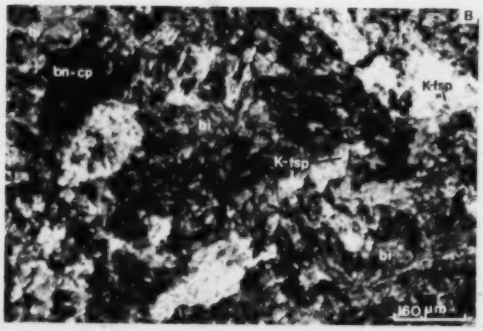
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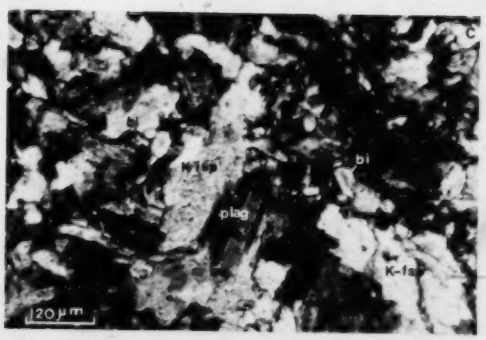
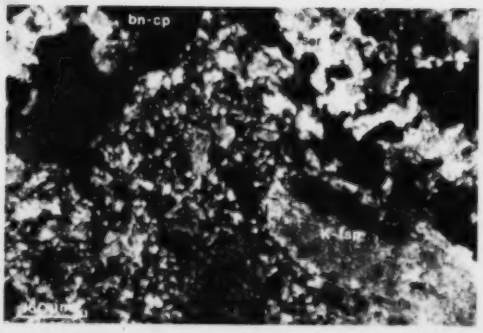
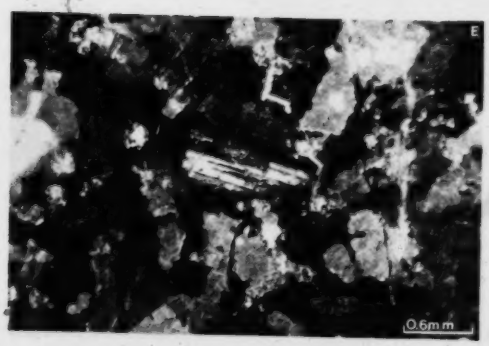
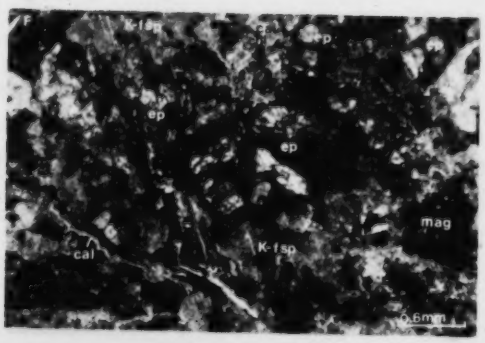
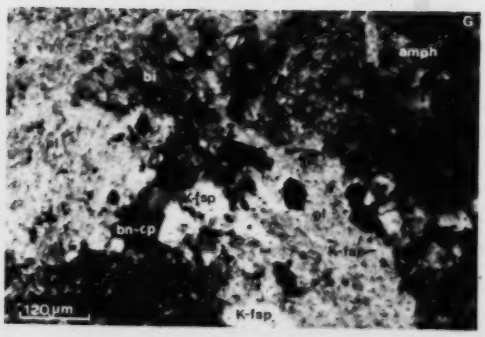
K-fsp
K-fsp
bi
160 µm


C
K-fsp
bi
plag
K-fsp
120 µm


bn-cp
K-fsp


E
0.6mm


F
K-fsp
ep
ep
ep
mag
cal
K-fsp
0.6mm


G
amph
bi
K-fsp
bn-cp
K-fsp
120µm
K-fsp

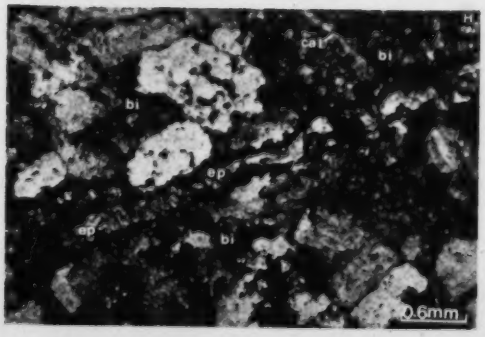

H
cal
bi
bi
ep
ep
bi
0.6mm

PLATE VI - 1 (cont'd)

H. Sample D.D.H. 72 - 8 (- 200 m)

Photomicrograph shows secondary biotite (bi) in low groundmass porphyry. Note that secondary biotite has partly replaced feldspar. Ore-bearing epidote (ep) veinlet cross-cuts biotite, both of which are cross-cut by microveinlet of calcite. (Transmitted light, nicols X)

PLATE VI - 2

PHOTOMICROGRAPHS OF ALTERED CHERRY CREEK ROCKS

Afton Copper Deposit, B.C.

A. Sample D.D.H. 72 - 10 (- 287 m)

Fine grained biotite (bi) - apatite (ap) intergrowth with associated disseminated chalcopyrite-bornite (black areas). (Transmitted light, nicols X)

B. Sample D.D.H. 71 - 2 (- 235 m)

Cherry Creek porphyry cross-cut by bornite (bn) - chalcopyrite (cp) - epidote (ep) veinlet, which has a narrow envelope of fine grained calcite (cal). (Transmitted light, nicols X)

C. Sample D.D.H. 73 - 32 (- 340 m)

Plagioclase phenocryst is altered to a fine grained mixture of epidote (ep), sericite (ser) and chlorite (chl). (Transmitted light, nicols X)

D. Sample D.D.H. 73 - 32 (- 615 m)

Secondary K-feldspar (K-fsp) microveinlet cross-cuts plagioclase phenocryst which is altered to epidote (ep), sericite (ser) and calcite. (Transmitted light, nicols X)

E. Sample D.D.H. 73 - 32 (- 615 m)

Photomicrograph shows rarely observed lensoid prehnite along secondary biotite cleavage. Prehnite is partly pseudomorphed by epidote. (Transmitted light, nicols X)

F. Sample D.D.H. 73 - 32 (- 340 m)

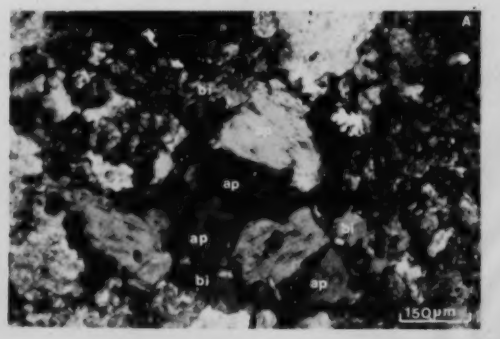
Amphibole is altered along cleavages to fine grained chlorite (chl). Calcite (cal) and pyrite (py) are also present as alteration products. (Transmitted light, nicols X)

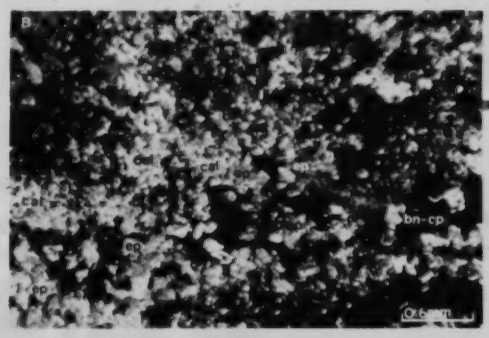
G. Sample D.D.H. 72 - 26 (- 281 m)

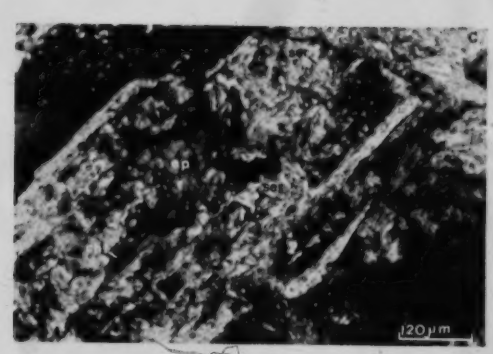
Healed Cherry Creek breccia with veinlet composed of chlorite (chl) and K-feldspar (K-fsp), both of which are cross-cut by late stage calcite (cal) microveinlets. (Transmitted light, nicols X)

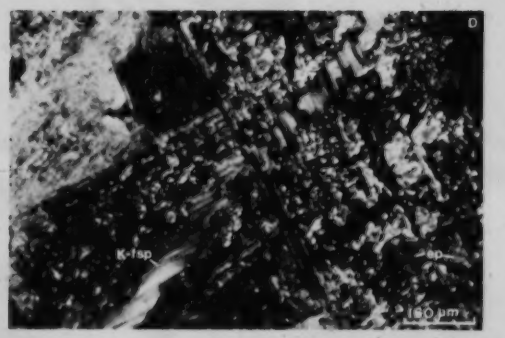
H. Sample D.D.H. 72 - 10 (- 20 m)

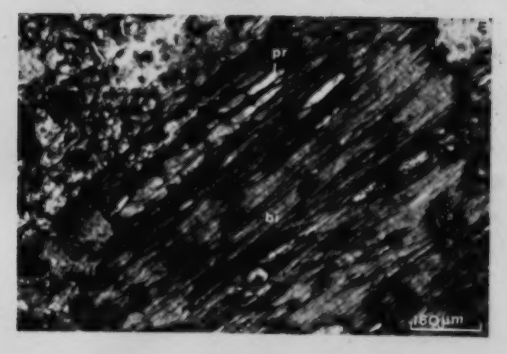
Calcite veinlet with fine grained chlorite displaying radiating and 'bow-tie' textures. (Transmitted light, nicols X)


A
bi
ap
ap
bi
ap
bi
150µm

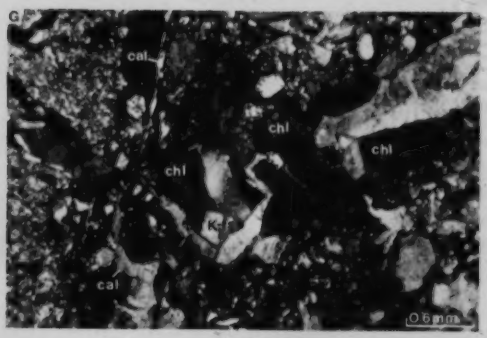

B
bn-cp
cp
ep


C
ap
120µm


D
K-fsp
ap
160µm


E
pr
bi
160µm

F
chl
chl
160µm


G
cal
chl
chl
chl
cal
0.6mm

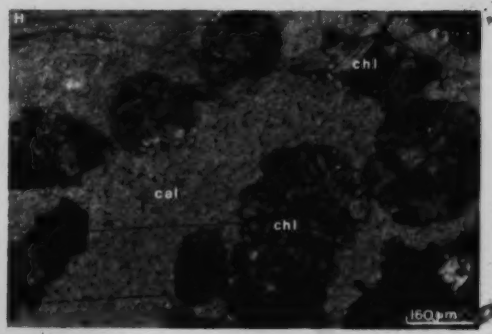

H
chl
cal
chl
160µm

PLATE VI - 3

PHOTOMICROGRAPHS OF ALTERED CHERRY CREEK ROCKS

Afton Copper Deposit, B.C.

A. Sample D.D.H. 72 - 10 (- 381 m)

Vug filling of late stage calcite (cal), vermicular and spherulitic chlorite (chl), and acicular zeolite (zeo) clusters. (Transmitted light, nicols X)

B. Sample D.D.H. 73 - 32 (- 448 m)

Veinlet composed of barite (bar) - quartz (q) - calcite (cal) - albite (ab). The assemblage is thought to have acted as a buffer on the supergene chalcocite (cc) - bearing solution. Note how chalcocite has partly replaced the gangue. (Transmitted light, nicols X)

C. Sample D.D.H. 72 - 10 (- 20 m)

Late stage calcite (cal) - chlorite (chl) - pyrite (py) assemblage in highly altered Cherry Creek porphyry. (Transmitted light, nicols X)

D. Sample D.D.H. 72 - 8 (- 238 m)

Late stage microveinlet of carbonate and chalcedonic quartz, cross-cutting mineralized (opaques) highly altered Cherry Creek porphyry. (Transmitted light, nicols X)

E. Sample D.D.H. 73 - 32 (- 160 m)

Disseminated pyrite (py) with propylitic/phyllic alteration. Specimen is composed essentially of chlorite (chl) and quartz - sericite mixture (light grey-white areas). Minor sphene (sph) is also present. (Transmitted light, nicols X)

F. Sample D.D.H. 72 - 26 (- 50 m)

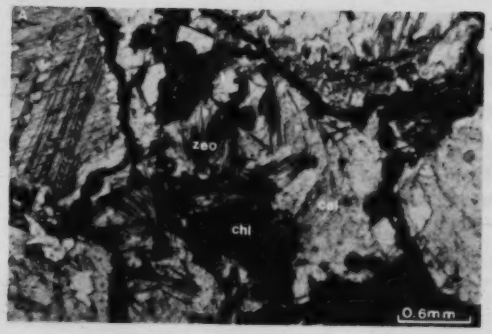
Typical late stage calcite (cal) - quartz (q) - pyrite (py) veinlet in propylitic pyritic halo. (Transmitted light, nicols X)

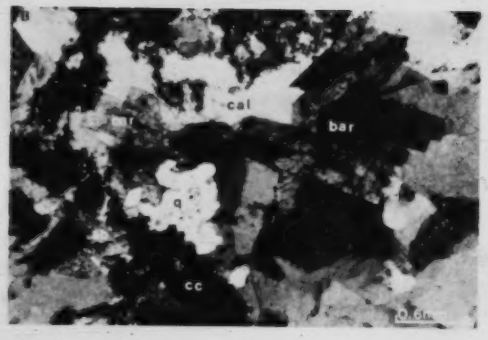
G. Sample D.D.H. 72 - 26 (- 68 m)

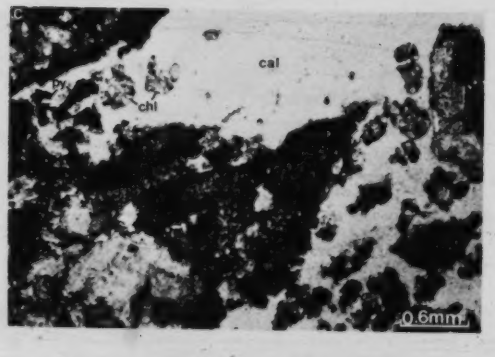
Photomicrograph shows relict amphibole (amph) and disseminated pyrite (py) in quartz-sericite alteration zone of the pyritic halo. (Transmitted light, nicols X)

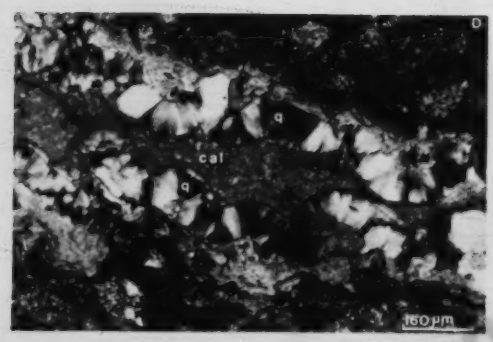
H. Sample D.D.H. 72 - 3 (- 20 m)

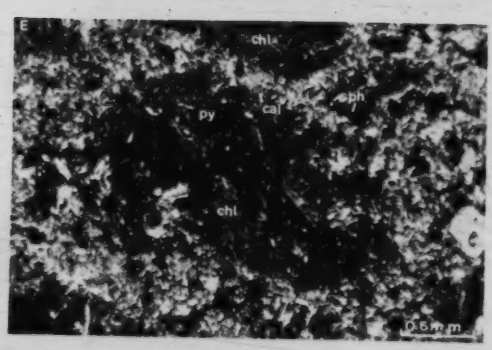
Photomicrograph shows goethite-chalcocite mineralization in fractured supergene-oxidation zone. (Transmitted light, nicols open)

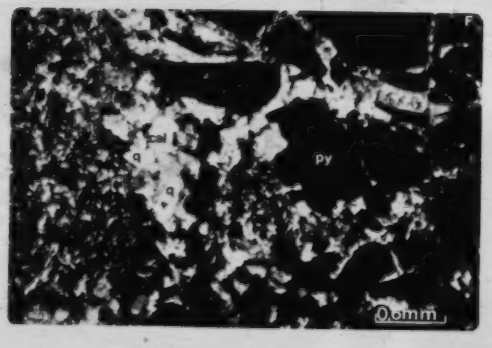

zeo
chl
0.6mm

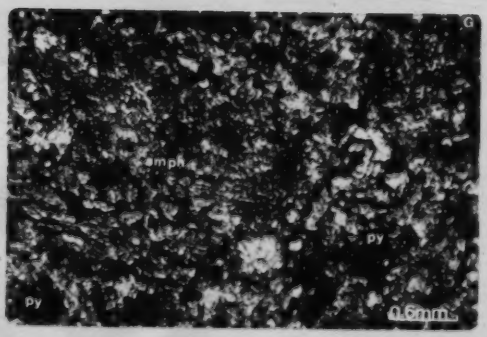

cal
bar
q
cc

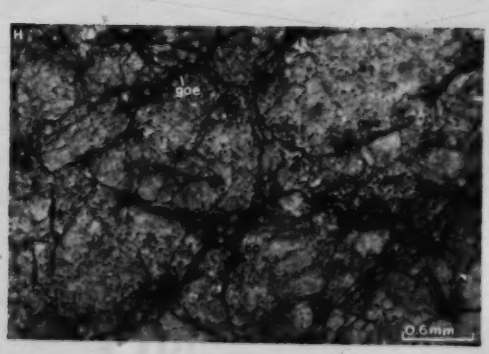

C
cal
chl
0.6mm


D
q
cal
q
160 µm


E
chl
py
cal
ph
chl
0.6mm


F
py
q
q
0.6mm


G
amph
py
py
0.6mm


H
goe
0.6mm

Chapter VII

GEOCHEMICAL STUDY OF THE AFTON COPPER DEPOSIT

A. INTRODUCTION

In this chapter geochemical data pertinent to the intrusive and ore forming environment of the Afton ore deposit are presented. Chemical nature of the volcanic and intrusive host rocks, chemical compositions of the ore-minerals, sulfur isotope compositions of the sulfides, and fluid inclusion studies are considered. This information, in conjunction with that of the preceding chapters, provides a basis for understanding ore-forming conditions.

B. CHEMICAL PETROLOGY OF NICOLA VOLCANIC AND ASSOCIATED INTRUSIVE ROCKS

The regional and local setting of the Afton deposit was discussed in Chapters II and III respectively. A considerable amount of chemical data has now been compiled (Barr et al., 1976; Preto, 1972, 1974, 1975a, 1975b) on the Intermontane Upper Triassic Nicola-Takla-Stuhini volcanic assemblages and associated plutonic rocks. The chemical data (Fig. VII - 1a) indicate that the volcanic rocks have a wide range of composition, ranging from alkaline through to subalkaline types, with the majority of the analyses plotting within the alkaline field. A major proportion of the Mesozoic volcanic succession in the Quesnel Trough (in which the Afton deposit is located) consists of potassium rich trachybasalt and tristantite with a lesser proportion of sodic types, which range from hawaiite to mugearite and trachyte (Barr et al., 1976). Subalkaline volcanic rocks range from basalt to rhyolite, with tholeiitic andesite and dacite most common.

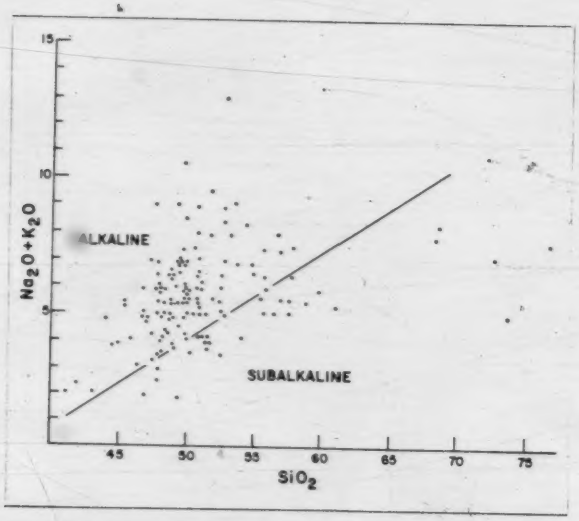


Fig. VII - 1a. Alkalis-silica (wt.%) plot for volcanic rocks of the Quesnel Trough. (After Barr et al., 1976)

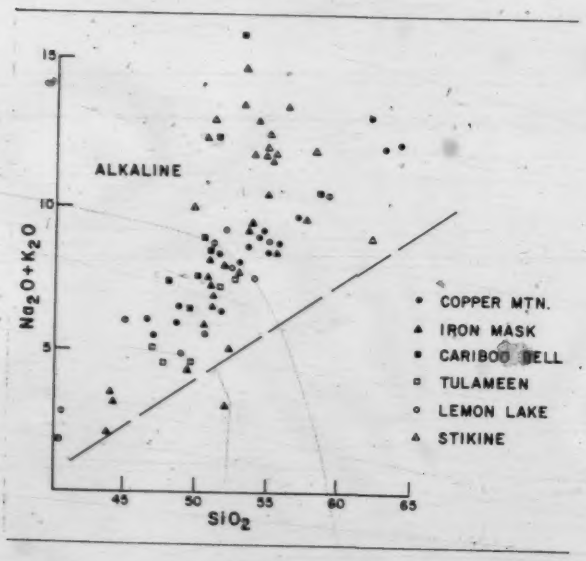


Fig. VII - 1b. Alkalis-silica (wt.%) plot for plutonic rocks of the Quesnel Trough. (After Barr et al., 1976)

An alkalis versus silica plot (Fig. VII - 1b) of unaltered Iron Mask rocks clearly establishes that these rocks are of alkaline affinity, and possess chemical compositions similar to the enclosing volcanic strata. This data therefore establishes the alkaline nature of the intrusive host rocks and further substantiates the contention that the Iron Mask suite of rocks are not only coeval with the enclosing volcanic rocks, but are of probable comagmatic origin.

C. CHEMICAL COMPOSITIONS OF THE IMPORTANT ORE BEARING MINERALS AND METAL DISTRIBUTION

1. Purpose

Hypogene and supergene copper-bearing minerals from the Afton deposit were investigated to confirm optical identifications and to establish the effects of supergene processes on hypogene ores; the chemical compositions of the ores and deviations, if any, from stoichiometry; and the existence of any minor or trace elements and associated growth zonation in native copper. Table VII - 1 outlines the sampling depth, vertical zonation, nature of mineralization, and color of the analysed phases in reflected light. The analytical procedure is outlined in Appendix VII - 1.

2. Analytical Results

The results of the investigation in wt.% and the derived mineral compositions are presented in Tables VII - 3 and VII - 4 respectively. Those analyses having wt.% totals outside the range of 100 $\pm$ 2% were considered unreliable (i.e. due to sample inhomogeneity, unanalysed

TABLE VII - 1

Electron Microprobe Sample Descriptions

D.D.H.	Sample No. (depth below surface)	Mineralization (in order of decreasing abundance)	Extent of Zone	Nature of Mineralization	Color in Reflected Light
72 - 8	-	Malachite-Azurite	0m - 26m (0' - 79')	Fracture Coatings	-
	-	Hematite-Magnetite	26m - 200m (79' - 600')	Veinlet, Disseminated	-
	-	Native Copper-Hematite-Magnetite	200m - 209m (600' - 626')	Fracture Filling, Veinlet, Disseminated	Cu: Deep Pink Mag: Grey Hm: Greyish
	# 7(226m, 667')	Bornite-Chalcopyrite-Chalcocite	209m - 231m (626' - 692')	Veinlet, Disseminated, Bleb	Bn: Pinkish Brown Cp: Yellow Cc: Whitish-Blue Tint
	#10(239m, 716')	Chalcopyrite-Bornite-Sulfosalt	231m - 239m (692' - 716')	Veinlet, Disseminated	Cp: Yellow Bn: Pinkish Brown Ss: Grey
	#12(275m, 825')	Bornite-Chalcocite Chalcopyrite	239m - 315m (716' - 945')	Veinlet, Disseminated	Bn: 1) Pinkish Brown 2) Purplish Tarnished Cc: Whitish-Blue Tint Cp: Yellow

TABLE VII - 1 (cont'd)

D.D.H.	Sample No. (depth below surface)	Mineralization (in order of decreasing abundance)	Extent of Zone	Nature of Mineralization	Color in Reflected
	#18(337m, 1012')	Chalcopyrite - Bornite - Unidentified Mineral	315m - 368m (945' - 1105')	Veinlet, Disseminated	Cp: Yellow Bn: Pinkish Brown
71 - 2	#27(235m, 704')	Bornite - Chalcopyrite - Unidentified Mineral	241m - 266m (642' - 798')	Small Lense	Bn: Pinkish Brown Cp: Yellow Unid: Grey Whitish-Blue Tint
72 - 7	#14(159m, 477') #17(190m, 570') #21(212m, 636')	Native Copper - Hematite - Magnetite	80m - 263m (240' - 788')	Fracture Fillings, Disseminations, Blebs	Cu: Deep Pink Hm: Greyish White Mag: Grey
72 - 9	# 5(51m, 152') # 8(87m, 260')	Native Copper - Hematite - Magnetite	29m - 87m (87' - 260')	Fracture Fillings, Disseminations, Blebs	Cu: Deep Pink Hm: Greyish White Mag: Grey

Cu - Native Copper; Mag - Magnetite; Hm - Hematite; Cc - Chalcocite;
Ss - Sulfosalt; Unid - Unidentified; D.D.H. - Diamond Drill Hole

elements, inclusions, surface effects, etc.). Eleven bornite grains (55 analytical points) gave totals within the range, with eight bornites giving totals over 100 wt.% and three grains giving totals under 100 wt.%. Of the eight chalcopyrite grains (40 analytical points) two analyses gave totals outside the accepted range, and of the six reliable analyses, five gave wt.% totals below 100 wt.% and one above. Two chalcocite grains (10 analytical points) gave results within the accepted limits, with totals slightly below 100 wt.%. Analysis of three sulfosalt grains (15 analytical points) gave wt.% totals slightly below the lower acceptability limits. Complete analysis for Cu, Fe, S, and Se and As were made on the foregoing specimens.

(a) Bornite

Bornites for which complete analyses were made all approach the ideal stoichiometric composition (Cu_5FeS_4). As shown in Table VII - 1, two homogenous varieties of bornite are present in the ore. One variety is normal pinkish brown whereas the other variety is distinctly purplish in reflected light and somewhat tarnished. No significant differrences between the two types are evident from the microprobe analyses. The average composition for the eleven bornite grains is $Cu_{4.99}Fe_{0.99}S_{4.04}$, with trace amounts of As and Se included with the sulfur value. Copper values range from $Cu_{4.91 - 5.02}$, iron from $Fe_{0.95 - 1.03}$, and sulfur from $S_{3.99 - 4.08}$.

Sample 12 bornite grains have a slight excess of Cu, and are deficient in Fe. Two of the bornite grains have excess S, with one grain containing stoichiometric sulfur. Bornites of sample 10 show the largest spread of copper values from deficient $Cu_{4.97}$ to excess $Cu_{5.02}$. Although

TABLE VII - 3

Results of Electron Microprobe Analyses,
Average Composition of Each Grain (in wt.%)

Sample No.	Wt.% Cu	Wt.% S	Wt.% Fe	Wt.% Se	Wt.% As	Total Wt.%	Cu/S
Bn 12/1	64.02	25.59	10.68	0.01	0.01	100.31	1.26
Bn 12/4	63.54	25.60	10.49	0.05	0.02	99.70	1.25
Bn 12/5	63.73	25.54	10.50	0.05	0.02	99.84	1.26
Bn 10/1	63.78	25.59	11.09	N.D.	N.D.	100.46	1.31
Bn 10/2	63.22	25.69	11.44	0.02	0.02	100.40	1.25
Bn 10/3	63.30	25.59	11.11	0.05	0.02	100.06	1.25
Bn 7/1	62.60	25.51	11.03	0.69	0.36	100.19	1.21
Bn 7/2	61.92	25.37	10.90	0.67	0.37	99.22	1.21
Bn 27/1	62.47	25.74	11.27	0.64	0.36	100.49	1.20
Bn 27/2	62.52	25.64	11.27	0.69	0.36	100.47	1.21
Bn 27/3	62.57	25.71	11.21	0.64	0.36	100.49	1.21
Cp 10/1	34.94	34.98	28.70	0.07	0.02	98.72	0.50
Cp 10/2	34.39	34.87	30.54	0.07	N.D.	98.87	0.50
Cp 10/3	35.28	34.65	29.55	0.03	0.71	100.22	0.51
Cp 27/1	33.95	34.48	29.34	0.55	0.37	98.69	0.53
Cp 27/2	34.18	35.08	28.34	0.64	0.34	98.58	0.49
Cp 27/3	34.22	34.94	29.40	0.91	0.43	99.91	0.49
Cp 7/1*	32.26	33.74	29.37	0.60	0.35	95.81	0.49
Cp 7/2*	32.26	33.74	29.78	0.62	0.34	96.73	0.48
Cc 12/1	79.40	20.21	00.22	N.D.	N.D.	99.83	2.00
Cc 12/3	79.24	20.21	00.22	N.D.	N.D.	00.66	1.98
Tet-Tn 10/1*	45.40	28.00	03.29	0.03	20.62	97.35	0.89
Tet-Tn 10/2*	45.48	28.31	02.44	0.02	20.49	96.73	0.86
Tet-Tn 10/3*	45.75	28.22	02.32	N.D.	29.93	97.22	0.86
Bn 12/5+	63.73	25.54	10.49	0.05	0.02	99.84	1.26
Bn 10/4+	63.32	25.66	11.13	0.05	0.02	100.18	1.24
Bn 10/5+	62.10	25.19	11.14	0.05	0.02	98.50	1.27

Bn - bornite; Cc - chalcocite; Cp - chalcopyrite; Tet-Tn - tetrahedrite-tennantite; N.D. - not detected; * - Analyses suspect; + - average assumed composition for Fe, As, Se.

TABLE VII - 3 (cont'd)

Sample No.	Wt.% Cu	Wt.% S	Wt.% Fe	Wt.% Se	Wt.% As	Total Wt.%	Cu/S
Bn 7/3+	61.47	25.05	10.92	0.67	0.37	98.78	1.20
Bn 7/4+	61.50	25.09	10.93	0.67	0.37	98.56	1.24
Bn 7/5+	61.21	25.12	10.96	0.67	0.37	98.33	1.21
Bn 18/1+	59.67	25.18	11.01	0.68	0.37	96.90	1.17
Bn 18/2+	59.58	25.78	11.05	0.67	0.36	97.44	1.16
Bn 18/3+	58.54	25.33	11.07	0.68	0.36	95.00	1.15
Bn 18/4+	60.15	25.09	11.06	0.68	0.36	97.33	1.19
Cp 10/4+	34.80	35.03	29.63	0.03	0.71	100.20	0.50
Cp 10/5+	34.83	34.90	29.74	0.03	0.71	100.21	0.49
Cp 18/1+	34.44	34.79	30.03	0.61	0.33	100.21	0.50
Cp 18/2+	34.62	35.06	30.04	0.61	0.33	100.67	0.50
Cp 18/3+	34.97	35.60	30.12	0.61	0.33	101.63	0.49
Cp 18/4+	34.98	35.52	30.17	0.61	0.33	101.61	0.49
Cp 27/4+	33.75	34.79	29.48	0.91	0.43	99.36	0.48
Cp 27/5+	34.00	34.97	29.57	0.91	0.43	99.88	0.49
Cc 12/4+	79.43	20.01	00.22	N.D.	N.D.	99.65	2.00
Cc 12/5+	78.92	20.19	00.22	N.D.	N.D.	99.33	1.98
Bn 27/4+	62.45	25.70	11.25	0.64	0.36	100.40	1.21
Bn 27/5+	62.48	25.62	11.27	0.64	0.35	100.37	1.21

Bn - bornite; Cc - chalcocite; Cp - chalcopyrite; Tet-Tn - tetrahedrite-tennantite; N.D. - not detected; * - Analyses suspect; + - average assumed composition for Fe,As, Se.

TABLE VII - 4

Structural Formulae and Stoichiometry of Cu - Fe Sulfides and Sulfosalt From the Afton Copper Deposit

Sample No.	Structural Formula	Mineral Name
Bn 12/2	$Cu_{5.03}Fe_{0.96}S_{4.0}$	Bornite
Bn 12/4	$Cu_{5.03}Fe_{0.95}(Se,S)_{4.02}$	Bornite
Bn 12/5	$Cu_{5.05}Fe_{0.95}(Se,S)_{4.01}$	Bornite
Bn 10/1	$Cu_{5.02}Fe_{1.00}S_{3.99}$	Bornite
Bn 10/2	$Cu_{4.97}Fe_{1.00}S_{3.00}$	Bornite
Bn 10/3	$Cu_{5.00}Fe_{1.02}(Se,S)_{4.01}$	Bornite
Bn 7/1	$Cu_{4.97}Fe_{0.99}(Se,As,S)_{4.07}$	Bornite
Bn 7/2	$Cu_{4.93}Fe_{0.99}(Se,As,S)_{4.06}$	Bornite
Bn 27/1	$Cu_{4.91}Fe_{1.01}(Se,As,S)_{4.08}$	Bornite
Bn 27/2	$Cu_{4.92}Fe_{1.01}(Se,As,S)_{4.07}$	Bornite
Bn 27/3	$Cu_{4.92}Fe_{1.01}(Se,As,S)_{4.08}$	Bornite
Cp 10/1	$Cu_{1.02}Fe_{0.95}(Se,S)_{2.03}$	Chalcopyrite
Cp 10/2	$Cu_{0.49}Fe_{1.01}(Se,S)_{2.01}$	Chalcopyrite
Cp 10/3	$Cu_{1.02}Fe_{0.97}(As,S)_{2.01}$	Chalcopyrite
Cp 7/1	$Cu_{0.98}Fe_{1.01}(Se,As,S)_{2.02}$	Chalcopyrite
Cp 7/2	$Cu_{0.97}Fe_{1.01}(Se,As,S)_{2.02}$	Chalcopyrite
Cp 27/1	$Cu_{1.08}Fe_{0.98}(Se,As,S)_{2.03}$	Chalcopyrite
Cp 27/2	$Cu_{1.00}Fe_{0.94}(Se,As,S)_{2.06}$	Chalcopyrite
Cp 27/3	$Cu_{0.99}Fe_{0.97}(Se,As,S)_{2.04}$	Chalcopyrite

Bn - bornite; Cp - chalcopyrite; Cc - chalcocite

TABLE VII - 4 (cont'd)

Sample No.	Structural Formula	Mineral Name
Cc 12/1	$(Cu, Fe)_{2.00}S_{1.00}$	Chalcocite
Cc 12/2	$(Cu, Fe)_{2.00}S_{1.01}$	Chalcocite
Tet-Tn 10/1	$(Cu, Fe)_{3.22}As_{1.15}S_{3.63}$	Tennantite
Tet-Tn 10/2	$(Cu, Fe)_{3.17}As_{1.14}S_{3.69}$	Tennantite
Tet-Tn 10/3	$(Cu, Fe)_{3.17}As_{1.16}S_{3.67}$	Tennantite
Bn 10/4+	$Cu_{4.99}Fe_{1.00}(Se,S)_{4.01}$	Bornite
Bn 10/5+	$Cu_{5.03}Fe_{1.01}(Se,S)_{3.97}$	Bornite
Bn 7/3+	$Cu_{4.91}Fe_{1.00}(Se,As,S)_{4.09}$	Bornite
Bn 7/4+	$Cu_{5.03}Fe_{1.00}(Se,As,S)_{4.07}$	Bornite
Bn 7/5+	$Cu_{4.92}Fe_{1.00}(Se,As,S)_{4.08}$	Bornite
Bn 18/1+	$Cu_{4.85}Fe_{1.02}(Se,As,S)_{4.13}$	Bornite
Bn 18/2+	$Cu_{4.80}Fe_{1.01}(Se,As,S)_{4.19}$	Bornite
Bn 18/3+	$Cu_{4.79}Fe_{1.03}(Se,As,S)_{4.18}$	Bornite
Bn 18/4+	$Cu_{4.88}Fe_{1.02}(Se,As,S)_{4.09}$	Bornite
Bn 27/4+	$Cu_{4.92}Fe_{1.01}(Se,As,S)_{4.07}$	Bornite
Bn 27/5	$Cu_{4.92}Fe_{1.01}(Se,As,S)_{4.07}$	Bornite
Cp 10/4+	$Cu_{1.01}Fe_{0.99}(As,S)_{2.02}$	Chalcopyrite
Cp 10/5+	$Cu_{0.99}Fe_{0.98}(As,S)_{2.02}$	Chalcopyrite
Cp 18/1+	$Cu_{1.00}Fe_{0.99}(Se,As,S)_{2.02}$	Chalcopyrite
Cp 18/2+	$Cu_{1.00}Fe_{0.98}(Se,As,S)_{2.02}$	Chalcopyrite
Cp 18/3+	$Cu_{1.00}Fe_{0.98}(Se,As,S)_{2.03}$	Chalcopyrite
Cp 18/4+	$Cu_{1.00}Fe_{0.98}(Se,As,S)_{2.04}$	Chalcopyrite

Bn - Bornite; Cc - chalcocite; Tet-Tn - tetrahedrite-tennantite;
+ - composition for Fe, As, Se, assumed.

TABLE VII - 4 (cont'd)

Sample No.	Structural Formula	Mineral Name
Cp 27/4+	$Cu_{0.98}Fe_{0.98}(Se,As,S)_{2.04}$	Chalcopyrite
Cp 27/5+	$Cu_{0.99}Fe_{0.98}(Se,As,S)_{2.04}$	Chalcopyrite
Cc 12/4+	$(Cu,Fe)_{2.00}S_{1.00}$	Chalcocite
Cc 12/5+	$(Cu,Fe)_{2.00}S_{1.01}$	Chalcocite

Cc - chalcocite; Cp - chalcopyrite; + - composition for Fe, As, Se, assumed.

the widest range of Cu values is observed in this sample, the grains are ± 1% of being stoichiometric in both Fe and S. The five bornite grains from samples 7 and 27 are all deficient in Cu and all have excess S. The Fe values for these five bornite grains are all ± 1% of being stoichiometric.

In Table VII - 5, the compositions of bornites from the supergene and hypogene zone of the Mina Esmeralda, northern Chile, together with bornites from the Afton deposit, are presented. Bornites of samples 10 and 12 are very similar in composition to the hypogene bornites described by Sillitoe and Clark (1969), with those of sample 10 exhibiting a slight deficiency of Fe and a slight excess of Cu. Trace amounts of Se and As were detected in these bornites. Variation of Cu and S at individual points within each grain is small. Of the 120 counts for Cu and S, which were analysed simultaneously, only 6 counts gave values outside the statistical counting error for sulfur. It is concluded that bornites of samples 10 and 12 are normal homogenous bornites with no significant microscopic or microscopic exsolution admixture or alteration effects present.

Sample 7 was taken below an oxidized zone in which abundant native copper is present. Bornites of this sample contain from 1.0 to 1.5 wt.% less Cu than those bornites identified as normal hypogene bornite. Bornite 7/1 has a composition intermediate between hypogene bornite and the anomalous bornites described by Von Gehlan (1964) and Sillitoe and Clark (1969). Bornite of sample 27 was also taken below an oxidized zone and like the bornite of smaple 7, shows a Cu deficiency of approximately 1.0 wt.% compared to stoichiometric bornite. No significant variation occurred within any grain of the two samples, with both Cu and S of all

TABLE VII - 5

Electron Microprobe Analyses of Hypogene Bornite and Anomalous Bornite, Copiapo District, Chile, and 'Low Cu' Bornite From the Afton Deposit, B.C.

Sample	Wt.% Cu	Wt.% Fe	Wt.% S	Wt.% Total	Locality, Sample Depth
Hypogene Bornite +++	63.06	11.84	25.79	99.69	Mina, Abundancia de Puquois, Chile*
Hypogene Bornite	63.40	11.62	25.87	100.89	Mina Esmeralda, Chile*
Hypogene Bornite	63.79	11.84	26.55	102.18	Mina Esmeralda, Chile*
Cu_5FeS_4	63.33	11.12	25.55	100.00	
Hypogene Bornite (ave. Bn10 Bn12)	63.60	10.89	25.60	100.09	Afton Mines Ltd., B.C.
Anomalous Bornite	61.13	12.06	27.80	100.99	Mina Esmeralda, Chile* 0.0m (0')
Anomalous Bornite	61.20	12.63	27.49	101.32	Mina Esmeralda, Chile* 10.0m (30')
Anomalous Bornite	60.80	11.40	26.20	98.40	Mina Esmeralda, Chile* 10.0m (30')
Anomalous Bornite	61.10	11.50	29.00	101.60	Mina Esmeralda, Chile* 10.0m (30')
Anomalous Bornite	61.50	11.50	26.50	99.50	Mina Esmeralda, Chile**
'Low Cu' Bornite 7/1	62.60	11.03	25.51	99.14	Afton Mines Ltd., B.C. 226m (677')
'Low Cu' Bornite 7/2	61.92	10.90	25.37	98.19	Afton Mines Ltd., B.C. 226m (677')

* Analyses from Sillitoe and Clark (1969).
** Analyses from Von Gehlen (1964).
+++ Bn - Bornite

TABLE VII - 5 (cont'd)

Sample	Wt.% Cu	Wt.% Fe	Wt.% S	Wt.% Total	Locality, Sample Depth
'Low Cu' Bornite 27/1	62.47	11.27	25.74	99.48	Afton Mines Ltd., B.C. 235m (704')
'Low Cu' Bornite 27/2	62.52	11.27	25.64	99.43	Afton Mines Ltd., B.C. 235m (704')
'Low Cu' Bornite 27/3	62.57	11.21	25.71	99.49	Afton Mines Ltd., B.C. 235m (704')
'Low Cu' Bornite 18/1	59.67	11.01	25.18	95.86	Afton Mines Ltd., B.C. 337m (1012')
'Low Cu' Bornite 18/2	59.58	11.05	25.78	96.41	Afton Mines Ltd., B.C. 337m (1012')
'Low Cu' Bornite 18/3	58.54	11.07	25.33	94.94	Afton Mines Ltd., B.C. 337m (1012')
'Low Cu Bornite 18/4	60.15	11.06	25.09	96.40	Afton Mines Ltd., B.C. 337m (1012')

* Analyses from Sillitoe and Clark (1969).
** Analyses from Von Gehlen (1964).
+++ Bn - Bornite

points being within the statistical counting error for these elements. The 'low Cu' bornites are optically identical to normal hypogene bornite. They do not display the yellowish brown color and anisotropism characteristic of the anomalous bornites described by Sillitoe and Clark (1969). No oxidation products such as idiate and covellite were found associated with these samples. However, bornites of both samples have suffered a degradation. They are surrounded by a narrow rim of chalcopyrite and contain abundant 'pseudo' microveinlets of chalcopyrite throughout (see Plate V - 1E). A very fine grained 'sulfosalt-like' phase is distributed non-uniformly throughout the bornite in close proximity to the rim of chalcopyrite. This unnamed phase, which forms irregular patches and blebs, in some instances occurs in both the chalcopyrite and bornite and as an intergrowth between the two. The same textural relationship was found in sample 18, which had the lowest counting rate for Cu. The slight copper deficiency of these bornites appears to bear some relationship to the presence of this phase. The unnamed mineral had significant counting rates on Se, giving totals as high as 5.21 wt.% Se. Values* for Cu (1.30 wt.%), Fe (2.15 wt.%) and S (17.96 wt.%) correspond to known analysis (Palach et al., 1944) for selenian sulfosalts of the Pb/Bi variety, which are known to be associated with Cu - Fe sulfides. Thus, based on its optical properties, known elemental concentrations, association with Cu - Fe sulfides, and presence of other sulfosalts with minor amounts of Se, the unnamed phase is thought to be some selenian sulfosalt. It, together with microscopic admixtures of other sulfosalts (tetrahedrite-tennantite) and/or direct substitutions of these elements at sites within the sulfide phase, are believed to account

* Wt.% average of three analyses.

for the presence of Se and As detected in the Cu - Fe sulfides. According to Rankama and Sahama (1950), the Se^{2-} is enriched in hydrothermal sulfides at elevated temperatures with the diadochical replacement of S^{2-} also occurring more readily at high as opposed to intermediate and low temperatures.

(b) Chalcopyrite

Chalcopyrite approaches stoichiometric $CuFeS_2$. The average chalcopyrite composition of sample 10, which contains hypogene bornite, is $Cu_{1.01}Fe_{0.98}(Se,S)_{2.01}$. The chalcopyrites of sample 10, although slightly deficient with respect to Fe, are considered to have been deposited as normal hypogene sulfides with bornite. They have no unusual optical properties, have ideal compositions, and are only associated with hypogene bornite.

The chalcopyrite associated with 'low Cu' bornite of sample 7 gave low wt.% totals due to the presence of unanalysed elements. Counting rates for Cu were however considerably lower than that for the hypogene chalcopyrite of sample 10, giving compositions with 2 wt.% lower Cu. Sample 27, which contained 'low Cu' bornite, and the selenian sulfosalt phase, has chalcopyrite with approximately 1.0 wt.% less copper compared to the other hypogene chalcopyrites. As with the associated 'low Cu' bornites, which contained an average of 0.67 wt.% Se and 0.35 wt.% As, chalcopyrites of samples 7 and 27 also contained higher concentrations of these elements (average 0.66 wt.% Se and 0.37 wt.% As) relative to the other hypogene chalcopyrites. The same explanations that accounted for the presence of Se and As in bornite, can be applied to chalcopyrite.

(c) Chalcocite, Tetrahedrite-Tennantite, and Native Copper

Chalcocite of sample 12 occurs as discrete homogenous grains and

as mottled subgraphic to club-like intergrowths with hypogene bornite (see Plate V - 4G). The chalcocite is stoichiometric in composition. No Se was detected in the chalcocite and minor Fe (0.22 wt.%) is included with the copper value.

The bornite-chalcocite intergrowths observed in sample 12 are non-oriented and are not the result of isometrically controlled exsolution first described by Schwartz (1928). Lamellar chalcocite-bornite was, however, observed in the occasional specimen at Afton, occurring with other complex intergrowths and interlocking club-like bodies of bornite-chalcocite. Such ideal compositions, textural relationships, and attendant hydrothermal alteration are all suggestive of primary processes. Phase relations in the Cu-S system show that digenite is not stable below 70° C (Barton, 1973) and that chalcocite is stable from below 103° C to 435° C, a temperature at which digenite-chalcocite solid solution becomes complete. Furthermore, bornite is known to exhibit extensive solid solution in the Cu-Fe-S system. Bornite-digenite solid solution becomes complete above 335° C. Exsolution of bornite-chalcocite and bornite-chalcopyrite beginning at temperatures of 225° C and 500° C respectively can result in the formation of such textures as noted in the Afton ores. Bornite-digenite-chalcocite (Plate V - 4G), bornite-chalcocite (Plate V - 4H), and bornite-chalcopyrite-chalcocite intergrowths, as discussed in Chapter V, may have resulted from primary exsolution and/or replacement processes. Carr and Reed (1976) and Preto (1972) all describe chalcocite at Afton as being entirely of supergene origin even though Reed, in a study of the Highmont deposit (Reed and Jambor, 1976) shows identical textures (Figures 8 and 9) to be of primary origin, and Carr (1956) describes bornite-chalcpyrite-chalcocite mineralization in other geneti-

cally and spatially related deposits of the Iron Mask batholith to be of primary origin. Sulfur isotopic composition of chalcocite is presented in the following section in order to help resolve the nature of its origin.

Tetrahedrite-tennantite was found in association with chalcopyrite in sample 10. Due to the presence of unanalysed elements (Ag, Sb), the sulfosalt analysis gave totals which were slightly below the 100 ± 2.5 wt.% acceptability range. The results, however, indicate that the sulfosalt in this sample is of the arsenian tennantite variety. It will also be noted that the associated chalcopyrite contains 0.71 wt.% As and substantiates the observation that local admixtures of sulfosalt phases and/or substitutions account for the small Se and As values in the ores. Such phases are considered likely hosts for Au and Ag, though further verification is warranted.

Several grains of native copper were scanned for Ag, Au, As, Sb, Bi, V, Co, Ni, Pb and the host rocks for S. The native copper was found to be homogenous and the host rock entirely devoid of sulfur.

As some of the elements were thought to be present in concentrations below the detectability limit (50 ppm) of the electron microprobe, further investigations were carried out by means of atomic absorption spectrophotometry. The extraction procedure is outlined in Appendix VII - 2. Analyses (Cu, Au, Ag, Pb, Zn, Se, As, Mo) were performed on a Perkin Elmer Model 306 atomic absorption spectrophotometer in the commercial laboratory of Resource Associates of Alaska, Fairbanks, Alaska. Results of the analyses are presented in Table VII - 6.

The distribution of the lelments conformed to anticipated patterns in light of the known ore mineralogy. Mo is present in trace amounts

TABLE VII - 6

Results of Atomic Absorption Spectrophotometry Analyses

D.D.H. Sample No.	Ore Mineral Assemblage	Elements Analysed (in ppm, unless otherwise indicated) Cu	Ag	Pb	Zn	Au	As	Mo	Se
73 - 32 # 1	Py*	71.00	1.5	20	76	0.1	-	-	-
73 - 32 # 9	Py	67.00	2.0	18	210	0.1	-	-	-
73 - 32 #20	Bn-Cc-Dg	4.70%	11.9	37	118	0.7	-	-	-
73 - 32 #28	Cc+Bn	3.40%	8.5	96	163	0.3	160	4	10
73 - 32 #33	Bn-Cp-Tet-Tn	1.90%	17.5	17	166	0.1	180	-	-
73 - 32 #36	Cp-Bn-Tet-Tn	0.06%	2.1	24	260	0.7	-	4	-
73 - 32 #38	Cp-Bn	8.40%	16.9	37	122	0.4	-	-	-
73 - 32 #12	Py	940.00	1.1	21	152	0.1	-	-	-
72 - 8 # 3	Cc-Cu	0.01	2.6	23	168	0.2	-	-	-
72 - 8 # 4	-	220.00	2.1	16	186	0.1	-	-	-
72 - 8 #11	Bn-Cp	2.40%	5.0	30	82	1.7	-	-	15
72 - 8 #20	Cp-Bn	0.03%	2.6	17	92	0.3	-	-	-
72 - 8 #21	Cpy	350.00	1.1	20	152	0.1	-	-	-
72 - 22 # 7	Cu-Mag	330.00	0.9	15	94	0.1	-	-	-
72 - 22 # 9	Cc	6.50%	13.3	34	200	10.0	-	-	50
72 - 22 #15	Cu-Cc	0.08%	9.7	28	360	0.9	-	-	-
72 - 22 #23	Bn-Cp	0.07%	2.6	27	186	0.4	-	5	-
72 - 22 #26	Bn-Cp	2.30%	8.4	54	191	0.1	-	-	-
72 - 22 #37	Cu-Mag	0.03%	1.8	21	200	0.1	-	-	-
72 - 10 # 2	Cu-Cc	0.06%	3.5	38	360	0.1	-	-	-
72 - 10 #16	Cc-Cu	10.00%	79.0	43	190	0.4	-	-	-
72 - 10 #20	Cc-Cu	0.03%	2.6	17	92	0.3	-	-	-
72 - 10 #30	Bn-Cp-Ss	120.00	0.5	22	130	0.1	-	-	-
72 - 10 #31	Cp-Py-Bn	0.07	15.5	190	440	1.7	-	-	-

* For key to abbreviations see Appendix VI.

and Ag and Au are present in both supergene and hypogene ore zones. Higher concentrations of Ag are related to higher concentrations of Cu and/or As. Average Au values for the analyses is 0.79 ppm*, with the highest Au values showing an affinity to a higher Se content in the ores. The distribution of Zn is sporadic and does not display any obvious pattern relative to the other elements. Higher values do, however, bear a relationship to zones with high Ag and As.

Phase relationships of sulfosalts and in the Cu- Fe - S system are known to be extremely complex. Electron microprobe studies of the important ore minerals at Afton has shown that the main copper-bearing sulfides all possess compositions close to their idealized formulae. Minor amounts of sulfosalts have been confirmed in the ores, intimately associated (exsolution and/or replacement) with the sulfieds. Small deviations from stoichiometry are related to the presence of Se and As and/or admixed sulfosalt phases in the sulfide phases. The presence of As and Se bearing phases is not considered to impose any environmental hazards in the area as all required Pollution Control Board permits were granted.

D. SULFUR ISOTOPE STUDIES

1. Theory and Background

Variation in the natural abundance of the four stable isotopes of sulfur are as follows: S^{32} = 95.1%; S^{33} = 0.74%; S^{34} = 4.2% and S^{36} = 0.02%. Because they are far more abundant than the other stable sulfur isotopes, and their amounts therefore easiest to measure accurately, S^{32} and S^{34} have been studied most extensively. Natural variations in the ratio S^{34}/S^{32} are found to be as much as $\pm$ 15%. However, in the

* Au values in these analyses were slightly higher than the 0.58 ppm average value quoted for the entire deposit (Carr and Reed, 1976).

troilite phase of meteorites, variation in the S^{34}/S^{32} ratio is so small that it is almost within the analytical precision of the isotopic measurements, being only $\pm$ 0.015% from a ratio of 0.0450045 (Macnamara and Thode, 1950). Hence the isotopic ratio from terrestrial sources of sulfur, such as sulfide orebodies, is expressed in comparison to a standard troilite phase of meteorites, commonly taken as that from the Canon Diablo meteorite (C.D.T.). The variation is conveniently expressed by S^{34} ‰ units as follows:

(1) . . .

$$\delta S^{34}_{\text{Sample}}(‰) = \frac{(S^{34}/S^{32})_{\text{Sample}} - (S^{34}/S^{32})_{\text{Troilite Standard}}}{(S^{34}/S^{32})_{\text{Troilite Standard}}} \times 1000$$

All calculations in S^{34} composition in this work are made with respect to the Cañon Diablo troilite standard.

An extensive amount of literature on the application of sulfur isotopes to the study of ore deposits has been compiled since the early works of Jensen (1957, 1959) and Kulp et al., (1956) first appeared. Prior to the classic work of Sakai (1968), interpretation of sulfur isotope data was employed mainly as an aid in determining the source of the mineralizing solutions and hence in discriminating sulfide deposits of various origins from one another. New advances by Sakai (1968) showed that the isotopic compositions of sulfide minerals may be influenced by the temperature and pH of the hydrothermal fluids. Extensions of Sakai's approach by Ohmoto(1972) has further shown the effects of the physico-chemical states (T°, pH, f_{O_2}, f_{S_2}, m_{Σ_S}, and $\delta S^{34}_{\Sigma_S}$) on sulfur isotopic compositions. The important contribution of this work now allows one to interpret sulfur isotope data on the basis of the physico-chemical state

of the ore fluids. Hence the initial and subsequent changes in the ore fluids should be reflected in the sulfur isotopic compositions of the minerals. The isotopic compositions and isotopic trend of sulfur in the sulfides of the Afton deposit will now be considered in view of these advances. The experimental procedure is outlined in Appendix VII - 3.

2. Results

Results of the isotope analyses are expressed in δS^{34} ‰ units according to equation (1) and are shown in Table VII - 9 together with sample descriptions. Sample enriched in S^{34} are isotopically heavy relative to the Canon Diablo troilite standard and have positive (+ ‰) per mil values; negative (- ‰) values indicate depletion of S^{34} relative to the standard.

Figures VII - 2 and VII - 3 illustrate δS^{34} variation for all samples analysed, as well as individual sulfide phases. The δS^{34} values for all Afton sulfides analysed range between + 1.76‰ and - 25.59‰ . At a 98% confidence level the δS^{34} values range from + 1.76‰ to - 9.38‰ . The mean δS^{34} value for all analysis is - 2.40‰ with a standard deviation of $\pm$ 4.24 ‰. If the chalcopyrite sample (δS^{34} = - 25.59‰), which displayed an extreme depletion in S^{34}, is excluded from the statistical treatment, the mean per mil value for the analyses is - 1.86 with a standard deviation of $\pm$ 2.38‰.

Generally, the sulfide minerals from other Cordilleran hydrothermal porphyry copper deposits of magmatic association exhibit a narrow range of δS^{34} values with mean per mil values near zero. As the δS^{34} value for mantle sulfur typically ranges between - 0.3 to + 0.3 per mil (Ault and Kulp, 1959; Thode, 1963) most workers postulate a deep level or mantle source for

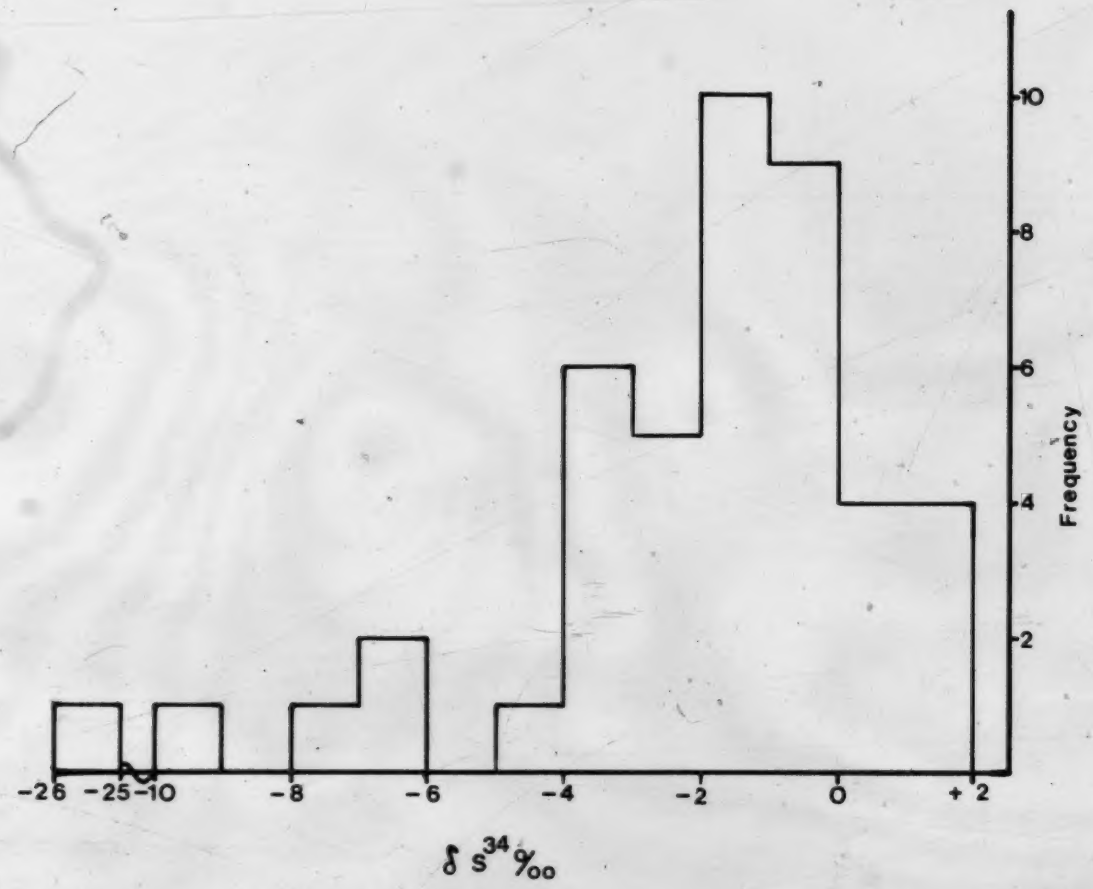


Fig. VII - 2 Variation of sulfur isotope compositions of sulfide minerals, Afton copper deposit, B.C.

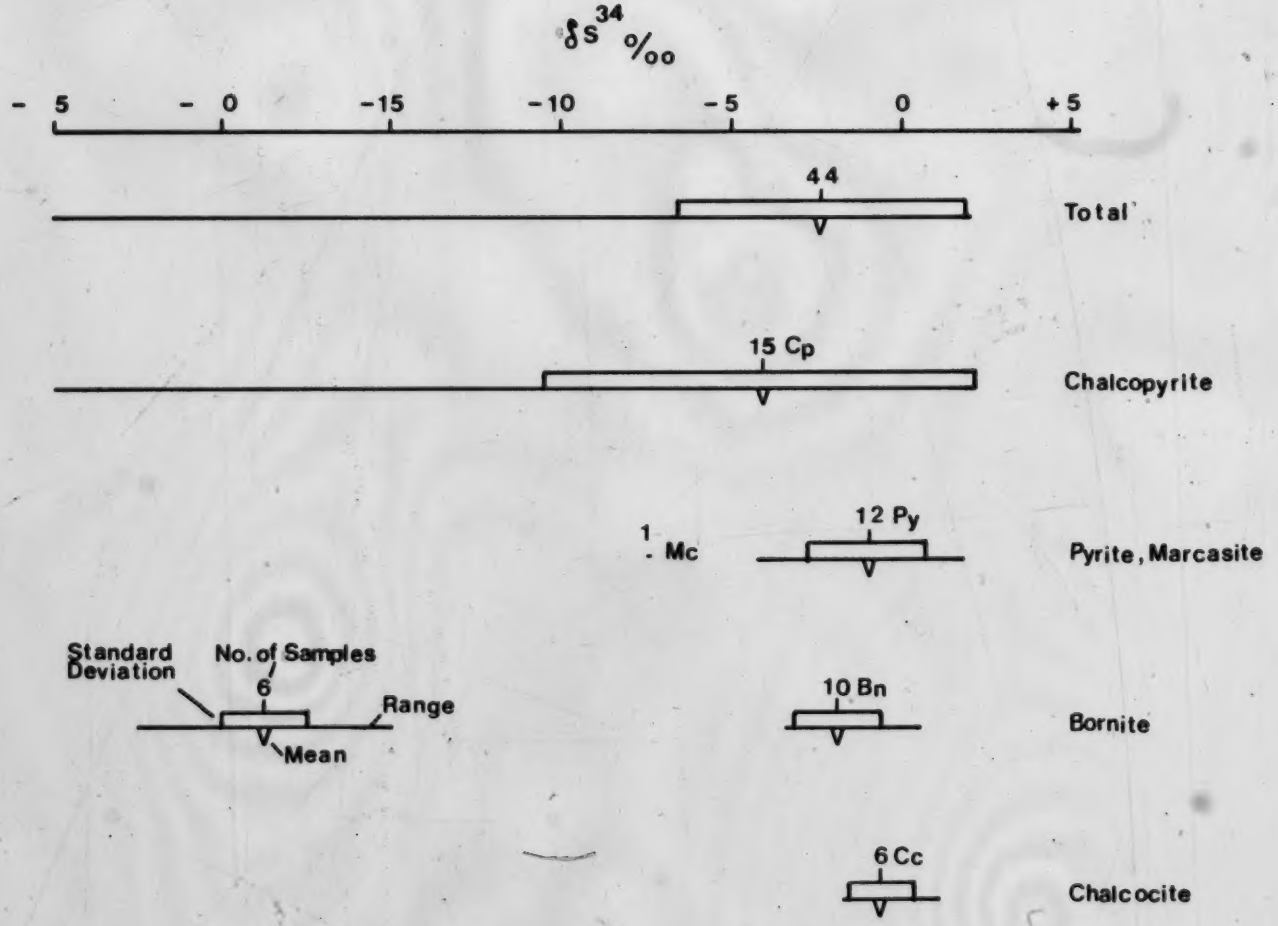


Fig. VII - 3 Mean, range, and standard deviation in isotope analyses of sulfide minerals, Afton copper deposit, B.C.

TABLE VII - 9

Sample Descriptions and Results (δS^{34} in ‰) of Sulfur Isotope Analyses, Afton Copper Deposit, B.C.

D.D.H. Sample No. Depth Below Surface	Zone	Ore Mineral Assemblage	Nature of Mineralization	Alteration Type: Stage No.	Mineral(s) Analysed	δS^{34} ‰
73 - 32 # 1 34m (103')	Pyritic Halo	Py	Vn	Prop:Stage 5a	Pyrite	- 1.12
73 - 32 # 6 97m (290')	Pyritic Halo	Py	Vlt/Bx	Prop/Phyl:Stage 5b	Pyrite	- 0.09
73 - 32 # 9 163m (490')	Pyritic Halo	Py	Diss	Prop:Stage 5a	Pyrite	- 0.39
73 - 32 #10 177m (530')	Pyritic Halo	Py-Cp> Tet-Tn	Vn	Phyl:Stage 5b	Chalcopyrite	- 6.98
73 - 32 #12 210m (630')	Pyritic Halo	Py-Cp	Vn/Bx	Prop/Phyl:Stage 5a	Pyrite Chalcopyrite	- 1.12 - 2.74
73 - 32 #20 373m (1118')	Hypogene	Bn ≥ Cc > Dg	Sub-Vlt/Diss	Prop:Stage 2	Bornite	- 3.48
73 - 32 #38 547m (1642')	Hypogene	Bn> Cp	Sub-Vlt/ u-Vlt	Prop:Stage 3b	Bornite Chalcopyrite	- 2.02
72 - 22 # 9 90m (270')	Supergene	Cc	F/Diss/Vlt	Prop:Stage 2/Pot: Stage 1/Sup	Chalcocite	- 1.71

For key to abbreviations see Appendix VI.

TABLE VII - 9 (cont'd)

D.D.H. Sample No. Depth Below Surface	Zone	Ore Mineral Assemblage	Nature of Mineralization	Alteration Type: Stage No.	Mineral(s) Analysed	δS^{34} ‰
72 - 22 #15 129m (386')	Supergene	Cu-Cc	Vlt	Prop:Stage 2/Sup	Chalcocite	- 1.77
72 - 22 #24 225m (674')	Hypogene	Cp > Bn	Sub-Vlt/Diss	Prop:Stage 2	Bornite Chalcopyrite	- 0.14 - 0.03
72 - 22 #26 259m (776')	Hypogene	Bn > Cp	Sub-Vlt/Diss	Prop:Stage 2	Bornite	- 2.48
72 - 22 #31 333m (1000')	Hypogene	Bn ≥ Cp	Vlt/Vlt/Diss	Pot:Stage 1/Prop: Stage 2	Bornite Chalcopyrite	- 3.07 - 2.34
72 - 22 #34 350m (1049')	Hypogene-Fault	Cp ≥ Py>> Bn	Diss	Phyl/Prop:Stage 5b	Chalcopyrite Pyrite	- 2.97 - 1.94
72 - 26 # 2 49m (147')	Pyritic Halo	Py - Cp	Diss	Phyl/Prop:Stage 5b	Chalcopyrite Pyrite	- 3.58 - 1.85
72 - 26 #10 81m (242')	Pyritic Halo	Py-Cp	Vlt/Bx	Phyl/Prop:Stage 5e	Chalcopyrite Pyrite	- 6.74 - 4.47
72 - 26 #15 106m (318')	Pyritic Halo	Py>> Cp	Vlt	Phyl/Prop:Stage 5c	Pyrite	- 1.30
72 - 8 # 9 228m (683')	Hypogene	Bn>> Cp	Sub-Vlt/Diss	Prop:Stage 3a	Bornite	- 0.58

For key to abbreviations see Appendix VI.

TABLE VII - 9 (cont'd)

D.D.H. Sample No. Depth Below Surface	Zone	Ore Mineral Assemblage	Nature of Mineralization	Alteration Type: Stage No.	Mineral(s) Analysed	δS^{34} ‰.
72 - 8 #12 275m (825')	Hypogene	Bn > Cc	Sub-Vlt/Diss	Prop:Stage 2	Bornite	- 3.01
72 - 8 #18 337m (1012')	Hypogene	Cp > Bn	Sub-Vlt/Diss	Prop:Stage 2	Bornite Chalcopyrite	- 1.87 - 1.08
72 - 8 #20 353m (1058')	Hypogene	Cp-Bn	Diss	Prop:Stage 2	Bornite	- 3.07
72 - 10 # 2 27m (81')	Supergene	Cc-Cu	F	Prop:Stage 3a/Sup	Chalcocite	- 0.83
72 - 10 #31 297m (892')	Hypogene	Cp > Py > Bn	Vn/Vlt	Prop:Stage 3a	Chalcopyrite Pyrite	+ 0.23 + 1.39
72 - 10 #33 317m (950')	Hypogene-Magnetite	Cp-Mc	Vn	Phyl/Prop:Stage 5c	Chalcopyrite Marcasite	+ 1.14 - 7.43
72 - 15 # 3 36m (109')	Supergene	Cc-Cu	Diss	Prop:Stage 3a/Sup	Chalcocite	+ 0.13
72 - 15 #18 156m (468')	Hypogene-Magnetite	Cp-Py	Vn	Prop:Stage 4/Phyl: Stage 5c	Chalcopyrite Pyrite	-25.59 - 4.00
72 - 15 #34 311m (932')	Hypogene	Cp > Py	Sub-Vlts	Prop:Stage 3a	Chalcopyrite Pyrite	- 0.84 + 0.35

For key to abbreviations see Appendix VI.

TABLE VII - 9 (cont'd)

D.D.H. Sample No. Depth Below Surface	Zone	Ore Mineral Assemblage	Nature of Mineralization	Alteration Type: Stage No.	Mineral(s) Analysed	δS^{34} ‰
72 - 17 #18 63m (188')	Pyritic Halo Magnetite	Cp≥ Py> Bn	Sub-Vlts	Prop:Stage 3a-4	Chalcopyrite Pyrite	- 9.38 + 1.76
72 - 18 #21 227m (682')	Hypogene	Cp> Bn	Diss/Bleb	Prop:Stage 3a	Chalcopyrite	- 0.85
72 - 3 #11 88m (263')	Supergene	Cc-Cu	F	Prop:Stage 2/Sup	Chalcocite	- 0.50
71 - 2 #13 103m (309')	Supergene	Cu-Cc	Sub-Vlt/Diss	Prop:Stage 3a	Chalcocite	+ 1.04
71 - 2 #27	Hypogene	Bn> Cp> Ss	Bleb	Prop:Stage 3a	Bornite	+ 0.58

For key to abbreviations see Appendix VI.

the sulfur in these deposits.

A deep level or mantle source for sulfur in the Afton deposit is postulated and is consistent with the probably deep source of Iron Mask and Cherry Creek magma based on Sr^{87}/Sr^{86} ratios. Cherry Creek syenite and Iron Mask diorite yielded Sr^{87}/Sr^{86} ratios of 0.70421 $\pm$ 0.00008 and 0.70398 $\pm$ 0.00006 respectively (Godwin, pers. comm.). These figures are in close agreement with those measured for oceanic rocks of mantle origin (Kesler et al., 1975; Hedge, 1974). Intrusions from continental margins have slightly higher Sr^{87}/Sr^{86} ratios of 0.705 to 0.710, while Precambrian crustal rocks have ratios of 0.720 to 0.750. Hence the Iron Mask-Cherry Creek suite developed from a source with low Sr^{87}/Sr^{86} ratios, such as reabsorbed oceanic crust or upper mantle. Evidence for oceanic crustal material in the Canadian Cordillera has been brought forth by Monger (1972).

An interesting feature borne out here is that the contrasting calc-alkaline Highland Valley suite of the same age and in the same general area as the Iron Mask-Cherry Creek alkaline suite display similar Sr^{87}/Sr^{86} ratios and similar δS^{34} per mil values for the associated sulfides. Chrismas et al., (1969) obtained δS^{34} values ranging from + 0.5‰ to - 9.8‰, with an average value of - 3.3‰, in a study of sulfides from the contact metasomatic Craigmont deposit, located at the periphery of the Guichon Creek batholith. The δS^{34} values from the Guichon Creek Valley Copper deposit also showed a narrow range of values from - 4.11‰ to + 1.53‰ (Osatenko and Jones, 1976). Low Sr^{87}/Sr^{86} ratios implied that the Guichon rocks, K-feldspar gangue and associated Craigmont mineralization were derived from a mantle source (Chrismas et al., 1969). McMillan (1976) also presents evidence for a deep seated source (upper mantle or subducted oceanic crust) for both Highland Valley magma and mineralizing solutions as well as other intrusive bodies and deposits of similar age in the Nicola belt.

Afton chalcopyrite and iron sulfide display the largest spread of values, with ranges from - 0.03‰ to - 25.59‰ and from + 1.76‰ to - 7.43‰, respectively. It will be noted (Table VII - 9) that the depletion in S^{34} of pyrite and chalcopyrite do not occur in the main stages of bornite-chalcopyrite ± pyrite mineralization. Coexisting hypogene chalcopyrite and bornite on both a sample and zonal scale exhibit a narrow range of δS^{34} values, from + 1.14‰ to - 3.48‰.

Chalcocite, from the shallow supergene native copper-chalcocite oxidation zone and from the deeper bornite-chalcocite zone, was analysed to see if the sulfur isotope values might provide a criterion for distinguishing between supergene and hypogene sulfides. Tudge and Thode (1950) have computed the partition function ratios of isotopic compounds of sulfur at 0° C and 25° C, and the values of the equilibrium constants for specific isotopic exchange reactions computed from these partition functions indicate supergene sulfate solutions will tend to be enriched in the heavier isotope. Hence, if chalcocite contains sulfur that was transported in the oxidation zone as sulfate solutions, then reduced to sulfide in the supergene zone, a trend of enrichment in the δS^{34}‰ values should be established. Supergene chalcocite at Afton displays a mean δS^{34}‰ value (- 0.61‰) that is slightly enriched in S^{34} relative to main stage hypogene bornite (mean per mil value = - 1.91) and chalcopyrite (mean per mil value = - 2.65) even though the values are within the standard deviation of the hypogene sulfides. Furthermore, the enrichment pattern is opposite to that established by Bachinski (1969) for the heavy isotope of sulfur under hydrothermal conditions. Bachinski (1969) has shown that the preference for the heavy isotope of sulfur among coexisting Cu-Fe sulfides should be in the order pyrite > pyrrhotite > chalcopyrite > bornite > chalcocite, which is in agreement with studies by Kajiwara and Krouse (1971) and

Sakai (1968). That is to say that if chalcocite in the supergene zone was deposited under hydrothermal conditions from the same parental sulfide solutions which deposited chalcopyrite and bornite, chalcocite theoretically should be depleted in S^{34} and display a trend of increasing $\delta S^{34}‰$ values relative to hypogene bornite and chalcopyrite. Although more analyses are warranted to fully substantiate this conclusion, preliminary indications reveal that δS^{34} values can distinguish hypogene and supergene sulfides at Afton.

Although the $\delta S^{34}‰$ values of the Afton deposit are generally comparable to those previously published for the porphyry type deposits (Field, 1966a, 1966b, 1973; Laughlin et al., 1969; Field et al., 1971; Jensen, 1971; Lange and Cheney, 1971; Chrismas et al., 1969; Osatenko and Jones, 1976) and thus on the basis of conventional geologic and isotopic criteria, metallization at Afton is a product of magmatic hydrothermal processes, a moderate to extreme enrichment of the lighter isotope, S^{32}, is present. Possible mechanisms to produce variations in the δS^{34} values of the hypogene sulfide minerals will now be considered.

3. Sulfur Isotope Geothermometry and Isotopic Trend of the Afton Deposit

Sulfur isotope geothermometry is based on the equilibrium sulfur isotope fractionations between coexisting sulfur-bearing compounds. Temperature dependent sulfur isotopic fractionations among the important sulfur species in hydrothermal solutions and sulfur-bearing minerals have been determined using both experimental and theoretical methods (Kajiwara et al., 1969; Kajiwara and Krouse, 1971; Sakai, 1968; and Czamanke and Rye, 1974). Curves derived by Rye and Ohmoto (1974) are shown in Figure VII - 4. The general trend of fractionation among coexisting phases is temperature dependent, decreasing as the

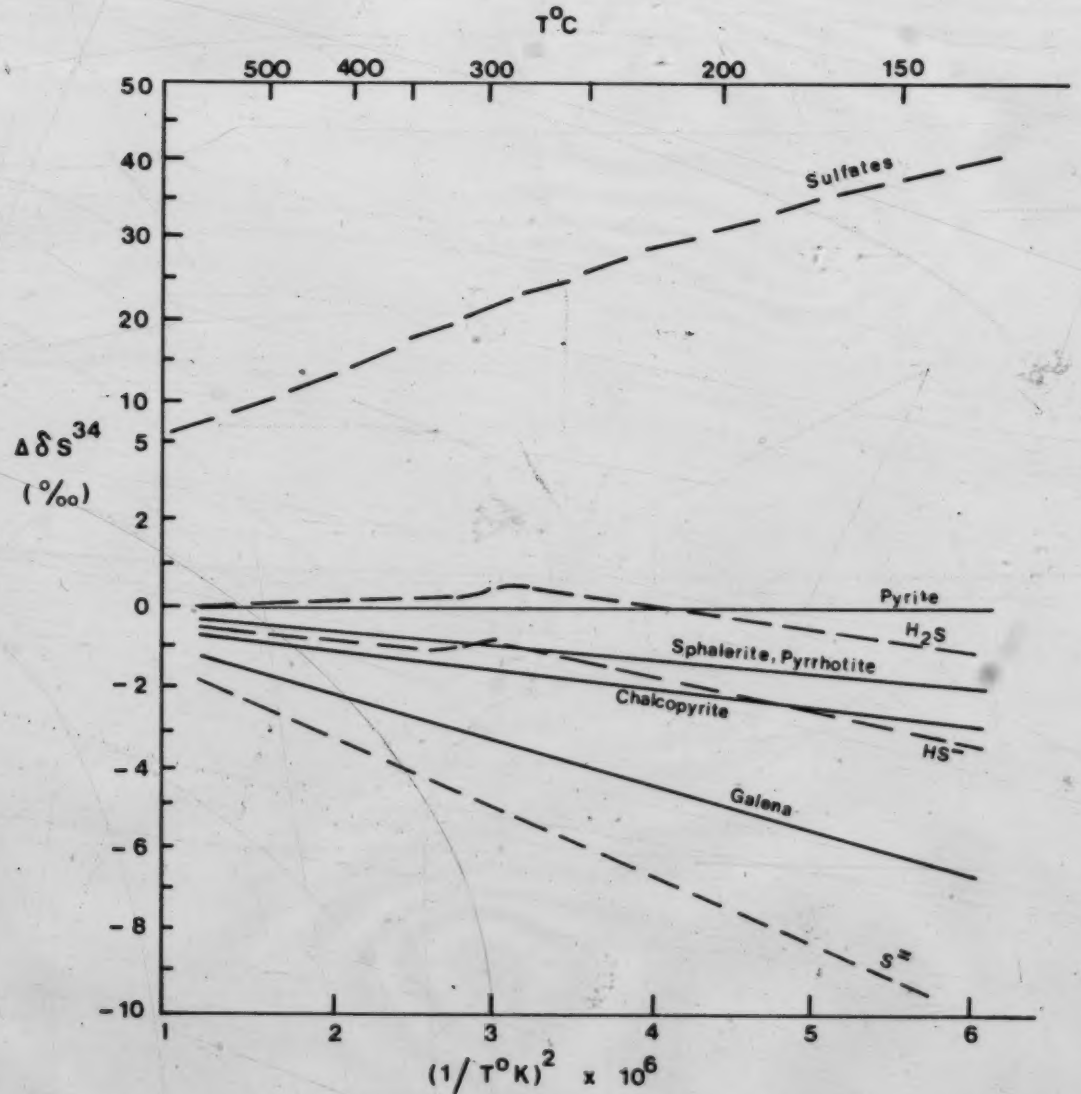


Fig. VII - 4 Sulfur isotope fractionations among sulfur species and sulfide minerals plotted with respect to pyrite. Dashed lines indicate aqueous species; solid lines indicate minerals. (after Rye and Ohmoto, 1974)

temperature increases. It is also apparent from Figure VII - 4 that the δS^{34} values of coexisting sulfides at any given temperature under equilibrium conditions should decrease in the order pyrite > sphalerite > chalcopyrite > galena.

The sulfur isotope fractionation factor ($\Delta \delta S^{34}_{x-y}$) for various mineral pairs or aqueous sulfur phases (x and y) are expressed as follows:

$$\Delta\delta S^{34}_{x-y} = \delta S^{34}_{x} - \delta S^{34}_{y}$$

$$= 1000 \ln \alpha x - y$$

The fractionation factor α is defined as:

$$\alpha = \frac{(S^{34} / S^{32})\ X}{(S^{34} / S^{32})\ Y}$$

The isotope fractionation factor of the pyrite-chlacopyrite pair is:

$1000 \ln \alpha$ py - cpy $= 4.5 \times 10^5 / T\ (^{\circ}K)^{-2}$ (Kajiwara and Krouse, 1971)

The larger the sulfur isotope fractionation between a given mineral pair, the more sensitive that pair will be as a sulfur isotope geothermometer. The order of sensitivity, as shown on Figure VII - 4 is: sulfate - sulfide > pyrite-galena > sphalerite (pyrrhotite)- galena > pyrite - chalcopyrite > pyrite - sphalerite. The bornite-chalcopyrite pair sulfur isotopic equilibrium according to any calculations, turns out to be similar to the sphalerite - pyrrhotite pair, that is $\Delta\delta S^{34}_{x-y}$ is too small to be a significant indicator of temperature. However, thermochemical data, as given by Bachinski (1969), shows that under equilibrium conditions, chalcopyrite is very slightly, though significantly, enriched in S^{34} relative to bornite.

Whether the application of sulfur isotope geothermometry to a particular ore deposit will give meaningful results depends upon the amount of known

geologic data and the availability of temperature sensitive sulfur-bearing mineral paris. The suitability of the Afton deposit to sulfur isotope geothermometry is considered poor due to the paucity of good temperature sensitive mineral pairs.

Eight coexisting chalcopyrite-pyrite and four bornite-chlacopyrite mineral pairs were analysed and the results are given in Table VII-10. Relative enrichment in S^{34} among six coexisting pyrite-chalcopyrite and four chalcopyrite-bornite pairs are entirely consistent with those established from theory or experiment (Sakai,1968; Bachinski, 1969; Kajiwara and Krouse, 1971). Isotopic temperatures have been determined from the delta values from the appropriate mineral pairs utilizing the experimental fractionation curve for pyrite-chalcopyrite (Kajiwara and Krouse, 1971) shown on Figure VII-5. Temperatures fall in the range of 172° C to 388° C which agrees with the temperature range (200° C to 725° C) cited for many other porphyry deposits (Creasey, 1968; Crerar and Barnes, 1976) and with temperatures given by Barton and Skinner (1967). According to Barton and Skinner (1967), the hydrothermal Cu-Fe sulfides, pyrite-chalcopyrite-bornite, coexist stably probably from below 230° $\pm$ 5° C where digenite exolves from bornite to 568° C where pyrite and bornite react to form isometric chalcopyrite and liquid sulfur. The textural evidence from bornite-chalcopyrite, which is suggestive of exsolution, and the isotopic temperatures derived from pyrite-chalcopyrite in the bornite-chalcopyrite $\pm$ pyrite ore zone, agree with the exsolution temperatures of 300° C, 475° C and 500° C established by Sugaki and Yamae (1950), Schwartz (1931) and Borchert (1934) respectively, though Barton (1970) and Brett (1964) caution the usefulness of such temperatures. The average temperature of 172° C is believed to represent the minimum equilibrium temperature for chalcopyrite-pyrite deposition in the peripheral pyritic halo. An average

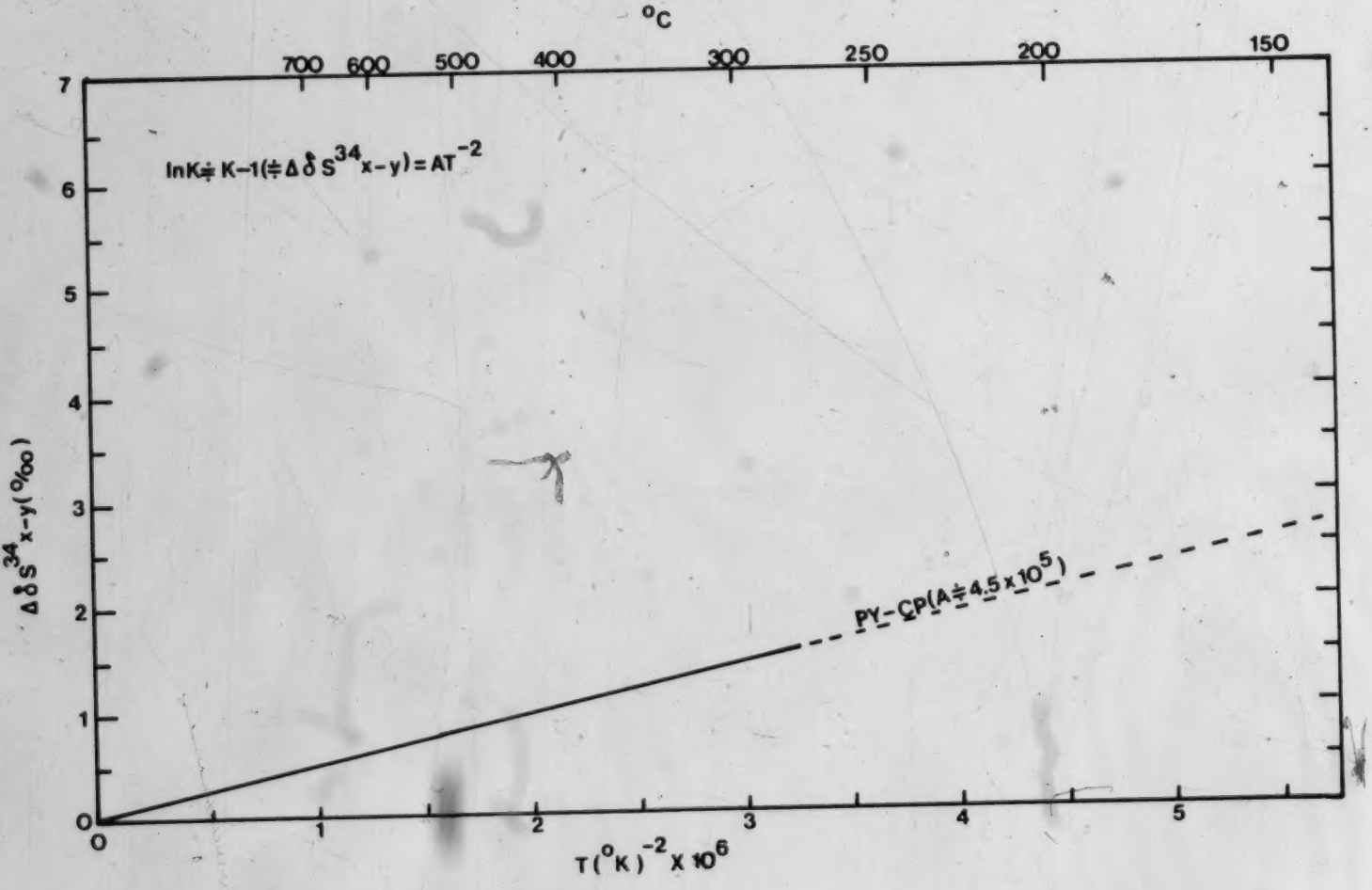


Fig. VII - 5. Geothermometric plot for the pyrite-chalcopyrite system. (After Kajiwara and Krouse, 1971)

TABLE VII - 10

Sulfur Isotope Compositions (δS^{34} in ‰) and Calculated Isotopic Fractionation Temperatures of Coexisting Cu - Fe Sulfides From the Afton Ore Deposit, B.C.

Sample No.*	Pyrite δS^{34}‰	Chalcopyrite δS^{34}‰	Bornite δS^{34}‰	$\Delta\delta S^{34}$ py - cp	Temperature (°C) Δ py - cp
73 - 32 #12	- 1.12	- 2.74	-	1.62	254
73 - 32 #38	-	- 1.75	- 2.02	0.26	-
72 - 22 #24	-	- 0.03	- 0.14	0.11	-
72 - 22 #31	-	- 2.34	- 3.07	0.73	-
72 - 22 #34	- 1.94	- 2.97	-	1.03	388
72 - 26 # 2	- 1.85	- 3.58	-	1.73	237
72 - 26 #10	- 4.47	- 6.74	-	2.27	172
72 - 8 #18	-	- 1.08	- 1.87	0.79	-
72 - 10 #31	+ 1.39	+ 0.23	-	1.16	350
72 - 15 #18	- 4.00	-25.59	-	21.59	-
72 - 15 #34	+ 0.35	- 0.84	-	1.19	342
72 - 17 #18	+ 1.76	- 9.38	-	11.14	-

* For Sample Descriptions See Table VII - 9 .

temperature of 360° C is derived from the Δ values of the three chalcopyrite-pyrite pairs from the hypogene ore zone. This temperature may however be somewhat low for the main period of bornite-chalcopyrite deposition. Beane (1974) obtained a temperature range of 450° C to 550° C for the bornite-chalcopyrite-pyrite biotite potassic zone at the Bingham, Utah, deposit, and a range of 350° C to 410° C from a similar assemblage at the Santa Rita deposit, New Mexico. Although other variables such as depth of formation influence temperature, bornite bearing biotite potassic zones in general form at relatively high temperatures (~400° C) in comparison to deposits with just chalcopyrite-pyrite mineralization.

Coexisting chalcopyrite-bornite pairs show consistent ($\Delta\delta S^{34}_{cpy - bn}$) sulfur isotopic fractionation with chalcopyrite slightly enriched in S^{34} relative to coexisting bornite. This is in agreement with the data of Bachinski (1969) and it is the contention of the writer that the isotopic fractionation and textural evidence collectively support an approach to equilibrium for the main part of hypogene bornite-chalcopyrite ± pyrite mineralization. Furthermore, the trend is consistent with isotopic fractionation effects that accompanied decreasing temperatures during the paragenetic and zonal evolution of metallization-alteration (i.e. from early bornite-chalcopyrite to later peripheral pyrite-chalcopyrite, as shown on Figure V - 1).

Although equilibrium conditions may have been approached during the main stages of ore deposition, extreme S^{34} depletion and possibly non-equilibrium conditions are apparent in the peripheral pyritic halo and paragenetically later pyrite-chalcopyrite mineralization. Two paragenetically later pyrite-chalcopyrite pairs (72 - 15 #18 and 72 - 17 #18) did not follow the predicted $\Delta\delta S^{34}_{py - cpy}$ enrichment pattern and therefore disequilibrium conditions

prevailed (i.e. they were deposited from solutions of different physico-chemical states). It should be noted that both pairs on the basis of texture did not really constitute a pair as they were composed of isolated grains, and therefore may reflect the isotopic trend of S^{34} depletion, rather than true disequilibrium conditions.

The outward and later decrease in per mil values, illustrated by chalcopyrite, and to a lesser extent by pyrite, and marcasite, is consistent with other examples of sulfur isotopic zoning in hydrothermal systems (see Field, 1966a; Greig et al., 1971; Thode et al., 1961; Chrismas et al., 1969; Rye et al., 1974). Sakai (1968) and Ohmoto (1972) have shown that the chemical state of hydrothermal fluids during ore deposition is controlled by the initial state, and by subsequent changes caused by reactions with wallrocks as well as previously deposited minerals. Changes in the chemical state (i.e. pH, T^{o} C, f_{O_2}, $\delta S^{34}_{\Sigma S}$) of the ore-forming fluids ideally should reflected in the sulfur isotope data as well as the ore mineralogy and alteration assemblages. The apparent isotopic trend of enrichment of S^{32} in chalcopyrite and the Fe-sulfides at Afton cannot be explained by a temperature decrease alone, and is thought to be controlled by other variables in the physico-chemical evolution of the ore solutions.

Mixing of an ore fluid with an inferred sulfur isotopic composition near zero ($\delta S^{34}_{\Sigma S} = 0$)* with light country rock sulfur is unlikely in view of the fact that the majority of the disseminated pyrite in the Nicola volcanics have δS^{34} per mil values near zero. Furthermore, a possible source for

*The indicated bulk composition of sulfur in the ore fluids is inferred to be close to the 0 per mil that is commonly accepted for magmatic hydrothermal sulfur (Rye and Ohmoto, 1974). The writer is unaware of any isotopic studies of porphyry copper deposits in which the inferred initial isotopic composition of the ore fluid is not close to zero.

light country rock sulfur, such as a limestone or greywacke bed, is all but lacking in the local geologic section.

Stabilities of many of the important ore minerals found in hydrothermal ore deposits have been determined (Barnes and Kullerud, 1961; Holland, 1965; Creara and Barnes, 1976). Ohmoto (1972) has shown that when the isotopic composition of a sulfur species i (δS^{34}_i) is compared with the stability fields of the minerals, then one can evaluate whether variations in f_{O_2} and/or pH can produce variations in the δS^{34} values.

In this regard, limits of pH and f_{O_2} of stage 5 chalcopyrite and pyrite mineralization is depicted on Figure VII - 6. A temperature in the order of 250° C is applied to late pyrite/chalcopyrite deposition as equilibrium temperatures of this order were obtained from temporally and spatially related pyrite-chalcopyrite assemblages. Indirect estimates of temperature also support a temperature of this magnitude. The occurrence of marcasite (δS^{34} = - 7.0‰) with late carbonate/zeolite implies that temperatures below 300° C were established as marcasite in the system, Fe-S, is not stable above this temperature (Barton and Skinner, 1967). Experimentally derived temperatures from later/peripheral zones of other porphyry systems (Nash and Theodore, 1971; Moore and Nash, 1974) are also in accord with a temperature of 250° C. Furthermore, at lower and higher temperatures (150° C to 350° C), the positions of the δS^{34}_i contours (Fig. VII - 7) with respect to the mineral boundaries are similar (Ohmoto, 1972).

The f_{O_2} and pH limits may be extrapolated from the alteration and ore mineral assemblages. The occurrence of calcite with copper and iron sulfides implies that conditions must have been to the right of the $CaCO_3$ insolubility curve (Fig. VII - 6). The presence of trace barite (and gypsum if it is indeed after anhydrite) in late propylitic carbonate vein assemblages shows

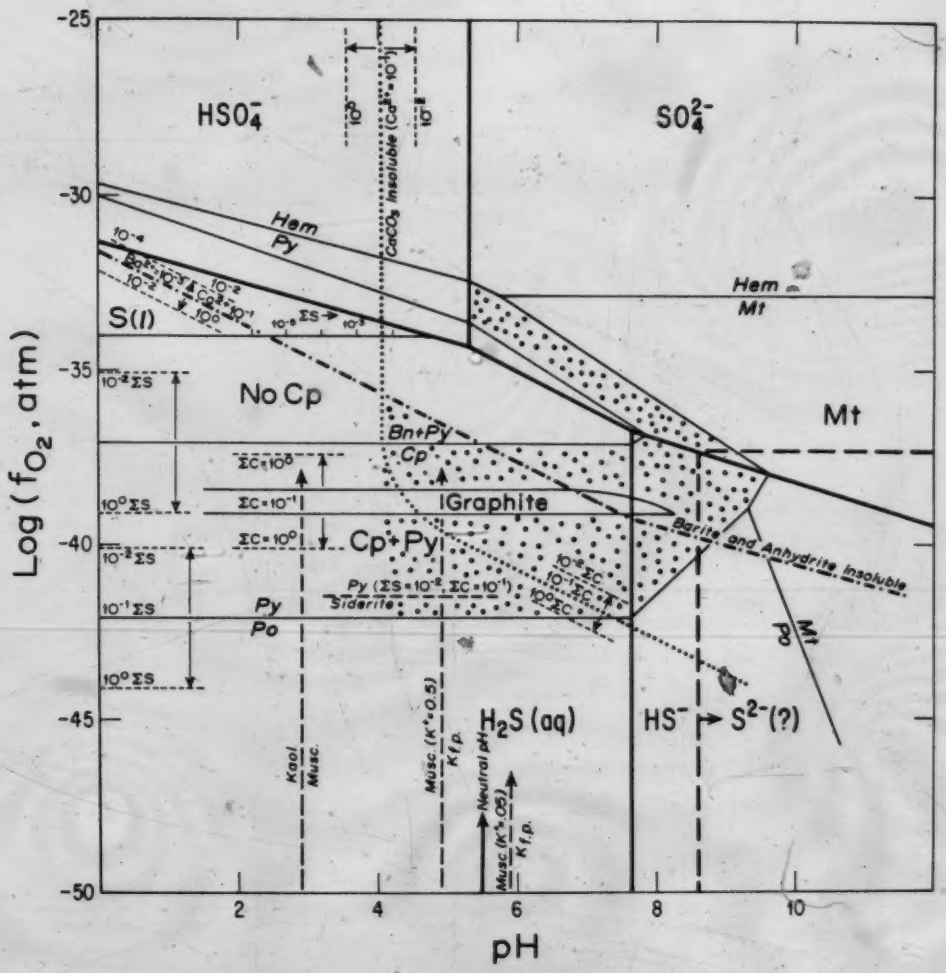


Fig. VII - 6. The f_{O_2}- pH stability fields of Cu-Fe-S-O minerals, calcite, barite, anhydrite, graphite, sericite, (muscovite) and aqueous sulfur species at 250° C, $\Sigma S = 0.1$. Dotted area outlines possible pH-f_{O_2} conditions of Afton pyrite-chalcopyrite assemblages. (Stability fields after Crerar and Barnes, 1976)

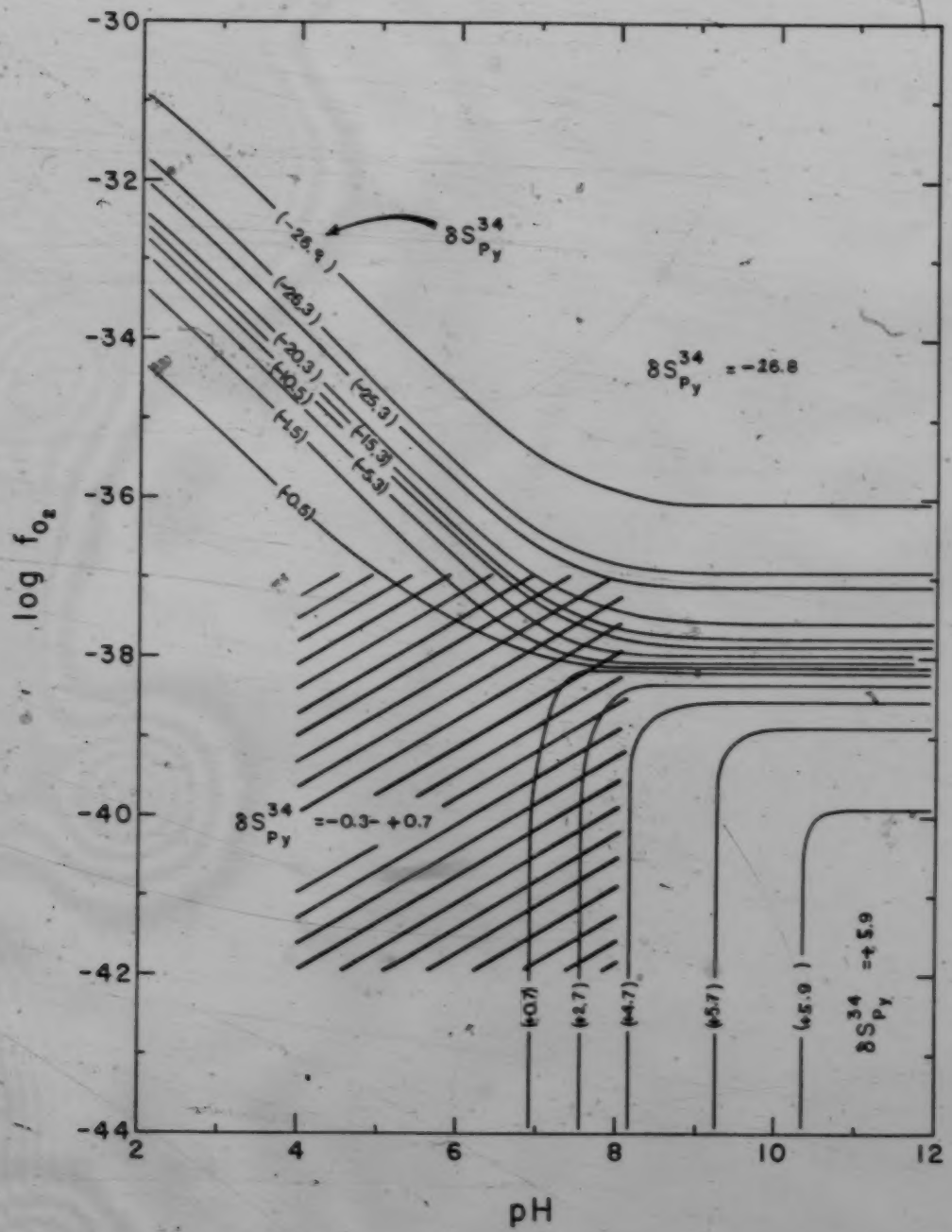


Fig. VII -7. Influence of f_{O_2} and pH on the isotopic composition of pyrite. T = 250° C, I = 1.0, and $\delta S^{34}_{\Sigma S}$ = 0‰. Dashed area represents pH-f_{O_2} conditions of Stage 5 pyrite deposition, Afton Mines, B.C. (For construction of diagram, see Ohmoto, 1972)

that conditions within barite/anhydrite saturation have been approached. A lower limit on the product of ΣS^* and f_{O_2} is fixed by the pyrite/pyrrhotite boundary, as pyrrhotite was not observed in any of the ore assemblages. Further constraints on ore depositions are provided by the bornite/chalcopyrite $\pm$ pyrite boundary as it encloses a region, bornite + pyrite, where chalcopyrite cannot exist and by the lack of graphite despite the appearance of carbonates in the gangue.

The pH limits are difficult to evaluate due to the wide pH range under which the relevant Cu-Fe sulfides are stable, and by further complications arising from the superimposition of supergene effects, which make inferrences on pH values from pH sensitive reactions (i.e. sericite-kaolinite) questionable. Approximate pH limits are, however, imposed by the $CaCO_3$ saturation curve and by the field of sericite stability, as pyrite + chalcopyrite + sericite + quartz assemblage lies within the field of sericite stability. More alkaline conditions are also present as K-feldspar appears to be stable in pyrite-bearing propylitic assemblages and coexistence of chlorite/zeolite are indicative of a relatively high pH$\sim$8 (Meyer and Hemley, 1967). Additional independent pH restrictions on ore fluids in terms of ore/alteration assemblages have been given by others (Hemley, 1959; Hemley and Jones, 1964; Meyer and Hemley, 1967; Shade, 1974). Probable pH limits for pyrite-chalcopyrite mineralization with associated sericite and/or propylitic alteration (i.e. chlorite-carbonate-zeolite-K-feldspar) at a temperature of 250° C, and other inferences cited herein, define a pH range from$\sim$4 to$\sim$8.

The pH - log f_{O_2} conditions extrapolated from the observed ore/alteration assemblages, brackets an area between pH of$\sim$4 to$\sim$8, and log f_{O_2} between the

* The total sulfur concentration in ore-forming fluids is generally considered to be between 0.1 and 0.001 moles/kg H_2O in the temperature range 150° C to 350° C (Ohmoto, 1972)

pyrite/pyrrhotite and chalcopyrite/bornite + pyrite boundaries (dotted area of Fig. VII - 6). Figure VII - 7 shows δS^{34}_i contours for pyrite (and chalcopyrite) precipitated at a temperature of 250° C from a solution with $\delta S^{34}_{\Sigma S} = 0‰$ and $\Sigma S = 0.1$ moles/kg H_2O, as adopted from Ohmoto (1972). The pH - f_{O_2} limits of the ore fluids are also delineated on Figure VII - 7.

It can be seen from Figure VII - 7 that pyrite and chalcopyrite precipitating from a solution with $\delta S^{34}_{\Sigma S} = 0$ per mil will exhibit δS^{34} values close to 0‰ in an area (as shown on Fig. VII - 6) in which H_2S is the dominant aqueous sulfur species. However, as illustrated by Ohmoto (1972), in the f_{O_2} - pH region where δS^{34}_i contours are clustered, δS^{34}_i values are highly sensitive to changes in f_{O_2} and/or pH, and will exhibit δS^{34} values of sulfide minerals much smaller than the $\delta S^{34}_{\Sigma S}$ value of the ore fluid. It is in the region of high f_{O_2} values, near the pyrite-magnetite and pyrite hematite boundaries, where the proportion of sulfate aqueous species becomes significantly large compared to the reduced H_2S aqueaous species. A change of f_{O_2} by one log unit can change the δS^{34} value of pyrite or chalcopyrite by nearly 20‰ at 250° C. It is therefore suggested that previously formed iron oxide minerals controlled the oxidation state of the later and lower temperature fluids. Local increases in the oxidation state of the ore fluid, caused by reaction with the Cherry Creek rocks containing abundant magnetite and/or hematite or possibly by reaction with oxidized meteoric water, are thought to be responsible for the observed isotopic trend. Although no measure of their original proportions beyond the present exposure are possible, sulfate/sulfide mineral ratios were presumably higher during the later stages of propylitic pyrite-chalcopyrite mineralization, as supported by the appearance of barite and gypsum (if it is after anhydrite). Alternatively, or in combination with this, it can be observed from Figure VII - 7 that minerals such as chalco-

pyrite and pyrite, which are stable over a wide pH region can exhibit a depletion of S^{34} by as much as 20‰ due to changes in pH by one unit.

Hence the isotopic compositions of Afton sulfides of main stage mineralization are similar to other Cordilleran hydrothermal deposits with magmatic associations which formed at relatively high temperatures in having near zero per mil values and small standard deviations. A deep mantle source for the sulfur in the sulfides is consistent with the probably deep source of the Cherry Creek and Iron Mask magma based on Sr^{87}/Sr^{86} ratios.

Temperature dependent isotopic fractionations indicate an average temperature of 291° C with a range of 172° C to 388° C. The geothermometric evidence also indicates that temperatures decreased from center to periphery and from early to late assemblages. The temperature decrease is partly responsible for the trend of S^{34} depletion. A slight enrichment in chalcocite in the heavier isotope is also consistent with theory and preliminary indications are that the hypogene and supergene sulfides may be distinguished by isotopic data.

The largest variation and S^{34} depletion occurred in the peripheral and paragenetically younger pyrite-chalcopyrite assemblages. The effects of low temperature, changing pH, and f_{O_2} over a large pH - f_{O_2} stability field during the later stages of mineralization, are thought to be reasonable explanations for the moderate to extreme depletion in S^{34}. Finally the consistent trend of S^{34} depletion, with paragenesis and zoning, suggests a restricted reservoir of sulfur in the hydrothermal system and would imply that the underlying magma chamber continued to be the predominant source of sulfur ($\delta S^{34}_{\Sigma s} = 0‰$).

E. FLUID INCLUSION STUDY

A study of fluid inclusions in pyrite-chalcopyrite veinlets was attempted in order to provide additional physico-chemical data on ore deposition and to provide a check on the isotopic temperatures derived in the preceding section. Forty-one polished plates and chips were prepared from stage 5 assemblages. After extensive observation and consultation (Dr. R.D. Morton and Dr. Say Lee Kuo, pers. comm.) it was apparent that none of the specimens contained inclusions of sufficient size or abundance to be amenable to freezing and heating experiments*. The following observations were, however, made. The fluid inclusions present were all of extremely small (< 10 μm) size with the smallest inclusions present in the quartz gangue. The majority of the inclusions were of secondary origin as they tended to be concentrated in planar clusters, cleavage planes, and linear zones. Three samples contained inclusions that were thought to be primary.

Secondary inclusions consisted either of two phase liquid-vapour (H_2O-vapour) types which were highly variable in their proportion of liquid:vapour, or single phase (100% vapour, 100% H_2O) types. All gradations were observed to be present in a single specimen. The primary liquid inclusions are of two phase liquid-vapour type which possess rather constant liquid:vapour ratios. The primary inclusions are composed of 70 to 80% liquid (H_2O) and 20 to 30% gas, though a low liquid-vapour ratio was noted in one inclusion. A three phase inclusion, consisting of vapour-liquid and daughter crystal of halite, was observed in one specimen.

* Access to better samples may be accomplished once the orebody is stripped.

Chapter VIII

SUMMARY AND CONCLUSIONS

The Afton porphyry copper deposit is one of many deposits in the Intermontane Belt of British Columbia which formed during the Upper Triassic - Lower Jurassic metallogenic epoch. The deposit is localized partly within the peripheral and younger Cherry Creek phase of the Cherry Creek - Iron Mask alkaline magmatic complex, and partly within the enclosing coeval Nicola volcanic rocks. The ore grade material (defined by 0.25% Cu cut-off) is centered within the Cherry Creek intrusive phases, whereas the Nicola volcanic rocks contain sub-ore grade pyritic mineralization.

The presently defined orebody consists of 30.84×10^6 tonnes of 1.0% Cu, 0.58 ppm Au and 4.19 ppm Ag. Mo is present only in trace amounts and Au and Ag are present in both supergene and hypogene ore zones. The orebody approximates a deltoid tabular body with a N 70° W strike and an average dip of 55° to the south.

Strong structural control, on both a regional and local scale, is indicated for the evolution of the intrusive phases and attendant hypogene and subsequent supergene mineralization. Structural data suggests that the Iron Mask complex was emplaced along a deep seated northwest trending zone of weakness, which is thought to be related to an ancient graben or rift system. Important local structures include major and minor north, northwest, northeast, and east trending faults, fault intersections, fracture zones and breccias. Important easterly and

northeasterly faults have controlled emplacement of the host Cherry Creek phase and hypogene mineralization. Recurrent movement, well into the Eocene, along several of these older faults is thought to have controlled the post hypogene structural pattern and had a marked influence on the supergene evolution of the deposit.

The tectonic framework of the Afton deposit, in terms of a plate tectonic model, is only partly understood. Why the Cu - Mo bearing Guichon Creek calc-alkaline batholith, set in a compressional framework, is so closely juxtaposed to the coeval Cu - Au alkaline Cherry Creek - Iron Mask complex set in a presumed tensional framework is as yet unresolved. Nielsen (1976) has suggested that deposits such as Afton may have developed in a region of back-arc spreading within an intra-arc or marginal basin east of a north to northwesterly aligned subduction zone.

The host Cherry Creek phase consists of several different textural varieties which have been emplaced in a complex array of small igneous intrusions, dyke-like bodies, and breccias, the exact dimensions of which are unknown. Composition ranges from diorite to syenite, with the more potassic members bearing a closer temporal relationship to metallization. Fine grained porphyritic textures are prevalent and are thought to have exerted a local control on mineralization. Equigranular varieties were confined to the deeper footwall portion of the orebody where they contained only marginal ore grade copper. The Nicola country rocks consist of a complex proximal succession of predominant volcaniclastic rocks which are believed to be indicative of an active volcanic centre in the immediate area. Radiometric dates and geologic evidence indicate that volcanism, intrusion, alteration and hypogene mineralization were closely related in both space

and time.

Depth of intrusion and resultant mineralization is not known to any degree of accuracy though features such as preintrusive fault control of emplacement, composite nature, late stage fine grained porphyritic phases with aphanitic groundmass, breccias, incorporation of country rock in border and roof zones, and close genetic and spatial relationship with volcanic rocks may be cited as criteria for a shallow volcanic to sub-volcanic environment. No more than 2.5 km of material was removed since the Upper Triassic in a type area just to the south of the deposit and this evidence, together suggests that depth of ore formation was in all likelihood $\leq$ 2.0 km, a figure commonly quoted for porphyry deposits of a similar nature (Brown, 1976).

Hypogene copper mineralization is in the form of veinlets, subveinlets, microveinlets, and disseminations, with veinlet and subveinlet controlled mineralization accounting for several orders of ore grade material relative to disseminations. A broad zonation, in regard to the predominant mode of occurrence of the hypogene ore minerals, from deep central disseminations, through veinlets, to peripheral veins, is present. A broad zonation of hypogene and supergene ore minerals is also apparent. A deep central hypogene copper ore zone consists of chalcopyrite-bornite with lesser amounts of sulfosalts. Within this zone the bornite : chalcopyrite ratio increases vertically to the base of the native copper-chalcocite blanket zone. Surrounding the main copper orebody is a peripheral zone, up to 700 m (2100') wide, of pyrite mineralization with subordinate chalcopyrite. A zone of magnetite is superimposed at the extreme eastern portion of the orebody.

The supergene zone of oxidation and enrichment, defined by native copper-

chalcocite mineralization, is confined to the upper 500 m (1500') of the orebody, though the base of the blanket is highly irregular, with structurally controlled digitations extending to considerable depth into the hypogene ore zone. Pronounced vertical zonation within the supergene zone is evident, with the lower portions defined largely by chalcocite ± native copper. The native copper : chalcocite ratio increases up dip to a point where only native copper mineralization is present, and there is a complete lack of primary ore and chalcocite in the zone.

The distribution of native copper and chalcocite bears a direct relationship to structural permeability. Prexisting structures and renewed shearing and fracturing related to Eocene uplift and block-faulting, coupled with an enhanced permeability and porosity as a result of hydrothermal alteration are thought to be major supergene controls. The zone of oxidation, defined by the presence of hematitic limonite with lesser copper oxides and carbonates, is largely coincident with native copper. Chalcocite persists below the zone of oxidation.

The apparent supergene zonation at Afton can readily be explained in terms of an Eh - pH diagram (Fig. VIII - 1a, VIII - 1b) showing mineral stability fields. Evidence has been cited that during the Eocene a combination of uplift, renewed fracturing, and a warm wet climate exposed the hypogene orebody to conditions of weathering and oxidation. Sato (1960) has shown that within the zone of oxidation, normal conditions are between pH 3 and 6 and Eh 0.4 to 0.8 volt. At Afton, conditions may have been more variable as the local presence of jarosite indicates highly acidic and oxidizing conditions, pH $\sim$ 3, and solutions in the presence of calcite will not exceed pH 8.3.

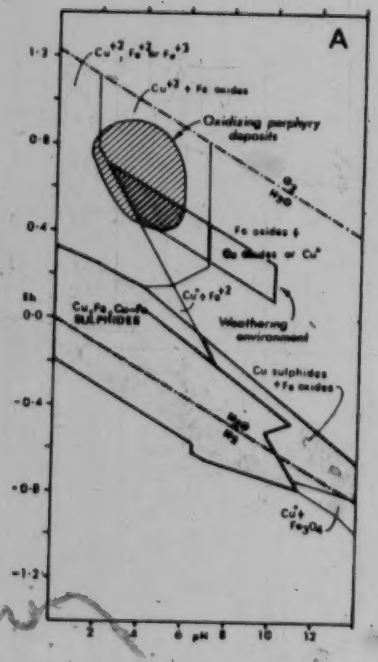


Fig. VIII - 1a. Mineral stability fields in the system Cu-Fe-S-O-H at 25° C, 1 atm. (After Garrels, 1960)

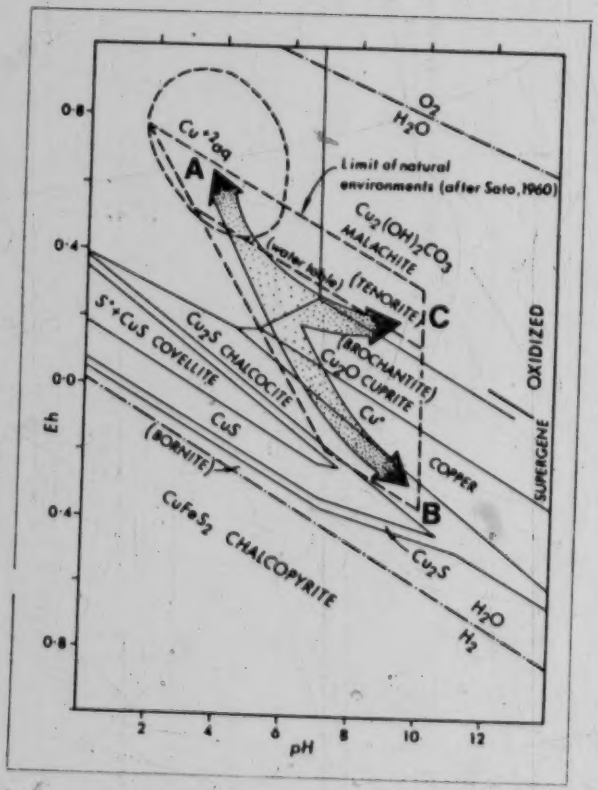


Fig. VIII - 1b. Paths of solutions in the zone of oxidation and supergene enrichment. Stability fields in Cu-H_2O-CO_2-O_2-S system at 25° C and 1 atm. (After Garrels, 1960)

The behavior of bornite and chalcopyrite, as well as other primary sulfides, in the zone of oxidation is fairly well established (Blanchard, 1968; Ney et al., 1976; Garrels, 1954; Anderson, 1955; Sato, 1960). In general, changes in the zone of oxidation involve freeing of the metal ions by oxidation of sulfide to sulfate. Solubility under the acid-oxidizing conditions at the ground surface is large. Copper, under such conditions, is highly mobile and is removed and transported downward in aqueous solution (oxidized meteoric water). Iron derived from the oxidation of bornite and chalcopyrite forms ferrous or ferric sulfate and is either precipitated in the zone of oxidation or is transported away. At Afton, where highly oxidizing conditions existed, hematite is the main limonite constituent, and has a stability field largely coincident with goethite, which is also present in the zone.

Enrichment at Afton involved the selective replacement of hypogene bornite and chalcopyrite by secondary chalcocite in the zone where potentials were lower and oxygenated and acid leach solutions were reduced and neutralized (Path A to B, Fig. VIII - 1b). The lower margin of the chalcocite blanket zone, as would be expected, is gradational to the underlying hypogene sulfide zone.

Formation of native copper took place under conditions sufficiently reducing to form native copper in preference to the Cu-oxides, but not sufficiently reducing to stabilize the sulfide ion. Continued oxidation and enrichment led to the encroachment and overlap of conditions within the native copper stability field with the chalcocite stability field, resulting in the observed native copper-chalcocite zone. Native copper formed from the oxidation of secondary chalcocite as the native copper :

chalcocite ratio increases with the proportion of hematitic limonite in the zone. Fluctuations and lowering of the water table during Eocene diastrophism is thought to be the main agent for the oxidation of chalcocite. Cu-oxides and carbonates formed with limonite in the zone of oxidation, possibly as a result of locally high CO_2 concentrations.

Descriptions and associations of the hypogene and supergene ore minerals were discussed in Chapter V and the paragenetic relationships were presented in Chapter VI. The available evidence indicates that alteration and metallization were spatially contemporaneous and coextensive. Although considerable overlap and telescoping is present, the writer was able to distinguish assemblages of propylitic, potassic and phyllic alteration. Eight pervasive and veinlet alteration stages, with accompanying mineralization, were recognized. Alteration zonation, from early deeper potassic grading outward through propylitic to phyllic is evident, but is by no means characteristic throughout. The bulk of the hypogene copper mineralization is coincident with propylitic, followed by potassic alteration.

Sulfur isotope analyses illustrate that the δS^{34}‰. values of the Afton deposit are comparable to other porphyry copper deposits of magmatic hydrothermal origin, in displaying a mean δS^{34} value close to zero and a small standard deviation. A deep source (upper mantle) for both Cherry Creek magma and Afton mineralization is proposed and is supported by Sr isotope as well as the geologic evidence presented herein.

Sulfur isotopic equilibrium fractionation among coexisting sulfides conformed to that predicted by experiment and theory. Enrichment in the lighter isotope, S^{32}, was in the order Py > Cp > Bn. Chalcocite from the supergene zone was enriched in S^{34} relative to the hypogene sulfides, indi-

cating that where other evidence is lacking, sulfur isotopes may be used to distinguish supergene from hypogene suflides.

The isotopic trend at Afton showed a moderate to extreme depletion in S^{34}, in peripheral and paragenetically younger stage 5 assemblages. Disequilibrium conditions, changes in pH or f_{O_2} were presented as alternative explanations to account for this trend.

Sulfur isotope geothermometry indicated that hypogene temperatures ranged from 172° C to 388° C, and that temperatures decreased from center to periphery. An average temperature of 291° C was obtained for all hypogene mineralization with a higher temperature of 360° C indicated for the main bornite-chalcopyrite ore zone.

As a concluding statement, the writer suggests the following lines of study should be pursued to further understanding of this rather unique deposit.

The available evidence as presented herein and by others (Carr and Reed, 1976; Preto, 1972) suggests that formation of native copper-chalcocite took place under supergene conditions sometime after formation of the hypogene ore zone. The possibility however exists that in such a high level volcanic to sub-volcanic environment in which this porphyry system evolved, conditions of oxidation may have been present during the hypogene hydrothermal event. Intersection or coincidence of the hydrothermal system with an Upper Triassic water table could provide such a mechanism. Conditions of oxidation would therefore be provided by Upper Triassic meteoric waters within the upper levels of the porphyry system. Variable liquid : vapour ratios, as noted in the fluid inclusions, may be cited as evidence for boiling and venting to the surface, and may be manifestations of such conditions. Further fluid inclusion work, in conjunction with the study of

D/H, O^{18}/O^{16}, and C^{13}/C^{12} (see Sheppard et al., 1971) may be able to distinguish an Upper Triassic magmatic-meteoric system from one that supposedly evolved under a different set of conditions during a later supergene event.

Trace and minor elements such as Se, As, and Hg may be useful pathfinders in the search for future deposits such as Afton. Their presence in anomalous amounts in both soils and water should be tested. This would also provide a check on any dangerous levels of selenium in the area. On the same note, the distribution of Au and Ag in the orebody is only partly understood and further investigations regarding their occurrence is warranted.

Lastly, the distribution and/or presence of U in the supergene zone should be tested as it is known to be associated elsewhere in British Columbia with Tertiary rocks similar to those which overlie the orebody. Furthermore, a U - Ag - Au association, if it exists, may reflect that conditions of oxidation and enrichment were indeed a post-Upper Triassic supergene event.

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Appendix IV

Cherry Creek Textural Nomenclature

Phenocryst to Matrix Relationship	
Phenocrysts not touching	High groundmass
Phenocrysts in point contact	Intermediate groundmass
Phenocrysts in edge contact (penetrating)	Low groundmass

Phenocryst Fabric	
Majority (>2/3) illustrating preferred orientation	Trachytoid or Fluxion
Some (1/3 to 2/3) illustrating preferred orientation	Sub-trachytoid or Sub-fluxion
No preferred orientation	Non-orientated
Phenocrysts in aggregates	Glomeroporphyritic
Two distinct phenocryst grain sizes present	Seriate

Grain Size	Composition (alkali feldspar : plagioclase)
≥ 1.5 mm	Diorite, Monzonite, Syenite
≃ 1.0 mm	Microdiorite, Micromonzonite, Microsyenite
0.3 to 0.5 mm	Andesite, Latite, Trachyte

Appendix VI

Key to Abbreviations

Minerals

Ab	albite
Ank	ankerite
Ap	apatite
Bar	barite
Bi	biotite
Bn	bornite
Cal	calcite
Car	carbonate
Cc	chalcocite
Cp	chalcopyrite
Chl	chlorite
Cu	native copper
Dg	digenite
Dol	dolomite
Ep	epidote
Goe	goethite
Gyp	gypsum
Hm	hematite
Ilm	ilmenite
Jar	jarosite
K	potassium
K-Fsp	K-feldspar
L	limonite
Mag	magnetite
Mc	marcasite
Ox	oxide
Py	pyrite
Prn	prehnite
Q	quartz
Ser	sericite
Sid	siderite
Sph	sphene
Ss	sulfosalt
Tc	talc
Tet	tetrahedrite
Tn	tennantite
Zeo	zeolite
Zo	zoisite

Alteration

Phyl	phyllic
Pot	potassic
Prop	propylitic
Sup	supergene

Miscellaneous

D.D.H.	diamond drill hole
Vn	vein
Vlt	veinlet
μ-Vlt	microveinlet
Diss	disseminated
Bx	breccia
F	fracture filling

Appendix VII - 1

Analytical Procedure

Specimens were mounted in cold-setting epoxy resin, polished using lead-lap techniques, and carbon coated. Analyses were performed on an ARL "EMX" microprobe using Wavelength Dispersive Detectors, a 15 Kv operating voltage, and a microbeam current of 100 nano-amperes. A spectrometer scan was used for detection of minor elements in native copper.

A list of the standards used and their compositions is given in Table VII - 2. Cu and S were determined against standard 1, Se against standard 2, and Fe and As against standard 3. Four 20 second counts were taken at five points across each grain analysed, and ten 20 second counts were made on standard peaks before and after sample readings. Five 20 second counts were made on either side of the analytical lines in order to determine background corrections.

Full corrections for atomic number, absorption, and characteristic fluoresence effects were made using a computer program, E.M.P.D.A.R. VII (Rucklidge and Gasparrini, 1969). Corrections for drift between successive calibrations and dead time corrections were made for all analyses.

TABLE VII - 2

Compositions of Standards Used
In Electron Microprobe Analyses

Standard #1	Cu %	Fe %	S%
EPS 22 - 5	35.00	35.50	32.50
(Synthetic Chalcopyrite)			
Standard #2	Se %		
EPS 20 - 4	100.00		
(Selenium Metal)			
Standard #3	Fe %	As %	S %
EPS 22 - 8	34.29	46.01	19.69
(Natural Arsenopyrite)			

Appendix VII - 2

Extraction Procedure for Atomic Absorption Spectrophotometry

1) Samples (4 - 5 Kg) were crushed, seived and homogenized using conventional techniques.
2) 2 gm samples were digested with 20 mls of aqua regia to $\frac{1}{2}$ volume, then made up to 20 mls with deionized water.
3) 10 mls of this solution was then shaken with 2 mls of DIBK and Aliquat 336 to extract the Au into the organic layer.
4) Au was determined from the extracted portion by atomic absorption spectrophotometry using background correction.
5) Ag, Cu, As, Se, Pb, Zn, and Mo were determined from the remaining 10 ml aqueous solution.

AA used : Perkin Elmer Model 306 equipped with deuterim arc background correction and electrodeless discharge power supply.

Appendix VII - 3

Experimental Procedure For Sulfur Isotope Analyses

1. Sample Selection, Separation, and Purification

A total of 44 sulfide samples were selected from the hypogene zone, pyritic halo, and supergene zone for sulfur isotope analysis. Sample locations (Table VII - 9, page 135) were thought to be representative of the various conditions of alteration-mineralization, from early to late and from center to periphery. Polished and polished thin sections of all samples were examined for mineral identification, homogeneity, and textural relationships.

Separation of pure mineral phases of chalcopyrite, pyrite, bornite, and chalcocite was performed by conventional techniques using heavy liquid gravitational separation (methylene tetrabromide and methylene iodide) and a Franz magnetic separator. Final purification was done by handpicking, with the purity of all mineral separates exceeding 95%.

2. Combustion Technique

Cuprous oxide (Fisher reagent grade) was used as the oxygen donor in the combustion of SO_2 gas. Prior to mixing, impurities were removed from the reagent by pre-heating for several hours under vacuum. Pure sulfide and Cu_2O were then ground to a fine powder in an agate mortar, weighed, and intimately mixed. A fixed sample weight* (a weight which would evolve

* FeS_2 = 14.997 mg., Cu_2S = 39.786 mg., $CuFeS_2$ = 22.94 mg., Cu_5FeS_4 = 31.36 mg.

250 μ moles of SO_2 gas) and a fixed molar ratio of O/S (O from Cu_2O, S from sulfide) of 4:1 or greater was maintained. The Cu_2O-sulfide mixture was packed between quartz wool in a small (OD: 0.8 cm) open ended quartz tube.

Combustion and collection of SO_2 gas from the sulfide-reagent mixture was carried out in a quartz-pyrex extraction line. The line consists essentially of a combustion chamber, pyrex tube vacuum line with three cold traps, two thermocouples, diffusion pump, mechanical pump, and breakseals. The sample cartridge was placed in a quartz tube, which was held in the combustion chamber, with the single open end of the quartz tube passing directly into the extraction line. The sample cartridge was then passed, by means of a magnet, into the evacuated combustion chamber. Combustion was carried out at a temperature of 1060° C for a period of 15 to 20 minutes. The evolved SO_2 gas and other trace gases such as CO_2 were trapped by liquid nitrogen in the second cold trap while H_2O was trapped in the first cold trap by a carbon tetrachloride-chloroform-dry ice slush. The SO_2 gas was then frozen into the second cold trap by replacing the liquid nitrogen with a mixture of n-pentane and liquid nitrogen held at a temperature of - 120° C. CO_2 expands during the freezing of SO_2 gas, and was pumped away together with any excess oxygen. The n-pentane and liquid nitrogen mixture was removed allowing the SO_2 gas to expand and be trapped in a graduated column by liquid nitrogen. Once isolated in the graduated column, the SO_2 yield measurement (in μ moles) was recorded. The SO_2 gas was then transferred to a standard breakseal and stored for analysis. The percentage yield of SO_2 gas for each sample is shown in Table VII - 7. All yields had to exceed at least 85% before isotopic measurement was

TABLE VII - 7

Yields of Sulfides Combusted at 1060° C

Atomic Ratio Oxygen (Cu_2O) : Sulfur = 4:1

D.D.H. Sample No.	Mineral	Sample Wt. (mg.)	Apparent Yield (μ moles)	Theoretical Yield (μ moles)	Temperature (°C)(average)	% Yield
73 - 32 # 1	Pyrite	14.59	228.00	243.27	23.50	93.24
73 - 32 # 6	Pyrite	14.39	220.00	239.94	23.25	91.30
73 - 32 # 9	Pyrite	14.52	225.00	242.12	23.00	92.61
73 - 32 #12	Pyrite	14.33	237.00	238.90	22.40	99.07
72 - 22 #34	Pyrite	14.89	231.00	248.28	22.85	92.11
72 - 26 # 2	Pyrite	14.66	220.00	244.44	22.50	89.81
72 - 26 #10	Pyrite	14.87	228.00	246.61	22.50	92.29
72 - 26 #15	Pyrite	14.46	224.00	241.10	23.00	92.80
72 - 10 #31	Pyrite	15.02	239.00	250.44	22.55	95.25
72 - 15 #18	Pyrite	14.95	227.00	249.28	23.10	90.75
72 - 15 #34	Pyrite	14.59	236.00	243.27	23.18	96.04
72 - 17 #18	Pyrite	15.10	230.00	251.78	22.87	91.08
72 - 10 #33	Marcasite	15.00	243.50	250.11	22.74	97.11
73 - 32 #10	Chalcopyrite	23.12	237.00	251.96	22.95	93.75
73 - 32 #12	Chalcopyrite	22.94	241.50	250.00	23.10	95.59
73 - 32 #38	Chalcopyrite	23.03	234.00	250.98	22.85	92.97

TABLE VII - 7 (cont'd)

D.D.H. Sample No.	Mineral	Sample Wt. (mg.)	Apparent Yield (μ moles)	Theoretical Yield (μ moles)	Temperature (°C)(average)	% Yield
72 - 22 #24	Chalcopyrite	23.19	225.00	252.73	22.66	88.83
72 - 22 #31	Chalcopyrite	23.87	237.50	260.14	23.17	90.94
72 - 22 #34	Chalcopyrite	22.91	241.50	249.67	22.90	95.76
72 - 26 # 2	Chalcopyrite	23.17	234.00	252.51	22.58	91.86
72 - 26 #10	Chalcopyrite	23.04	250.00	251.09	23.10	99.20
72 - 8 #18	Chalcopyrite	24.80	238.00	270.27	22.85	87.82
72 - 10 #31	Chalcopyrite	22.87	217.00	248.26	23.67	97.41
72 - 10 #33	Chalcopyrite	23.12	234.00	251.96	22.40	92.74
72 - 15 #18	Chalcopyrite	23.04	234.00	251.09	22.65	92.99
72 - 15 #34	Chalcopyrite	22.76	241.00	248.04	23.42	96.04
72 - 17 #18	Chalcopyrite	23.04	230.00	251.09	22.49	91.46
72 - 18 #21	Chalcopyrite	22.79	213.00	248.37	22.80	85.53
73 - 32 #20	Bornite	31.75	234.00	253.08	24.20	91.77
73 - 32 #38	Bornite	30.84	239.00	245.83	22.80	97.22
72 - 22 #24	Bornite	31.52	245.00	251.25	23.60	96.97
72 - 22 #26	Bornite	31.34	242.00	249.81	22.27	96.78
72 - 22 #31	Bornite	31.78	247.00	253.32	22.59	97.32
72 - 8 # 9	Bornite	31.60	242.00	251.88	23.80	95.50

TABLE VII - 7 (cont'd)

D.D.H. Sample No.	Mineral	Sample Wt. (mg.)	Apparent Yield (μ moles)	Theoretical Yield (μ moles)	Temperature (°C)(average)	% Yield
72 - 8 #12	Bornite	31.87	250.00	254.04	24.10	97.71
72 - 8 #18	Bornite	30.43	232.00	242.56	22.30	94.90
72 - 8 #20	Bornite	31.29	237.50	249.41	23.40	94.13
71 - 2 #27	Bornite	30.80	240.00	245.51	22.10	97.72
72 - 22 # 9	Chalcocite	40.51	246.50	254.55	23.40	96.38
72 - 22 #15	Chalcocite	39.27	237.00	246.76	23.00	95.07
72 - 10 # 2	Chalcocite	41.10	244.50	258.82	22.75	93.59
72 - 15 # 3	Chalcocite	40.31	239.00	253.29	24.10	93.06
72 - 3 #11	Chalcocite	39.68	238.00	249.33	23.58	94.95
71 - 2 # 3	Chalcocite	39.89	242.00	250.65	22.50	95.73

considered. The majority of the yields exceeded 90%.

3. Mass Spectrometer Measurement

Sulfur isotope analyses were performed on a 12' radius of curvature, 90° sector magnetic-analyzer gas source mass spectrometer. Prior to isotope analyses the isotope composition of the lab standard or working line standard (Fisher reagent grade SO_2 gas) was calibrated against the composition of various other SO_2 standards with established δS^{34} values with respect to Cañon Diablo troilite. The results of the calibrations are listed in Table VII - 8 and the derived correction formula, which is applied to all analysis, is as follows:

$$\delta S^{34}_{C.D.T. - x} = \delta S^{34}_{L.S. - x} \times 1.158 + 4.5$$

where $\delta S^{34}_{C.D.T. - x}$ = δS^{34} of unknown (x) versus δS^{34} of Cañon Diablo troilite (C.D.T.)

and $\delta S^{34}_{L.S. - x}$ = δS^{34} of unknown (x) versus δS^{34} of line standard (L.S.)

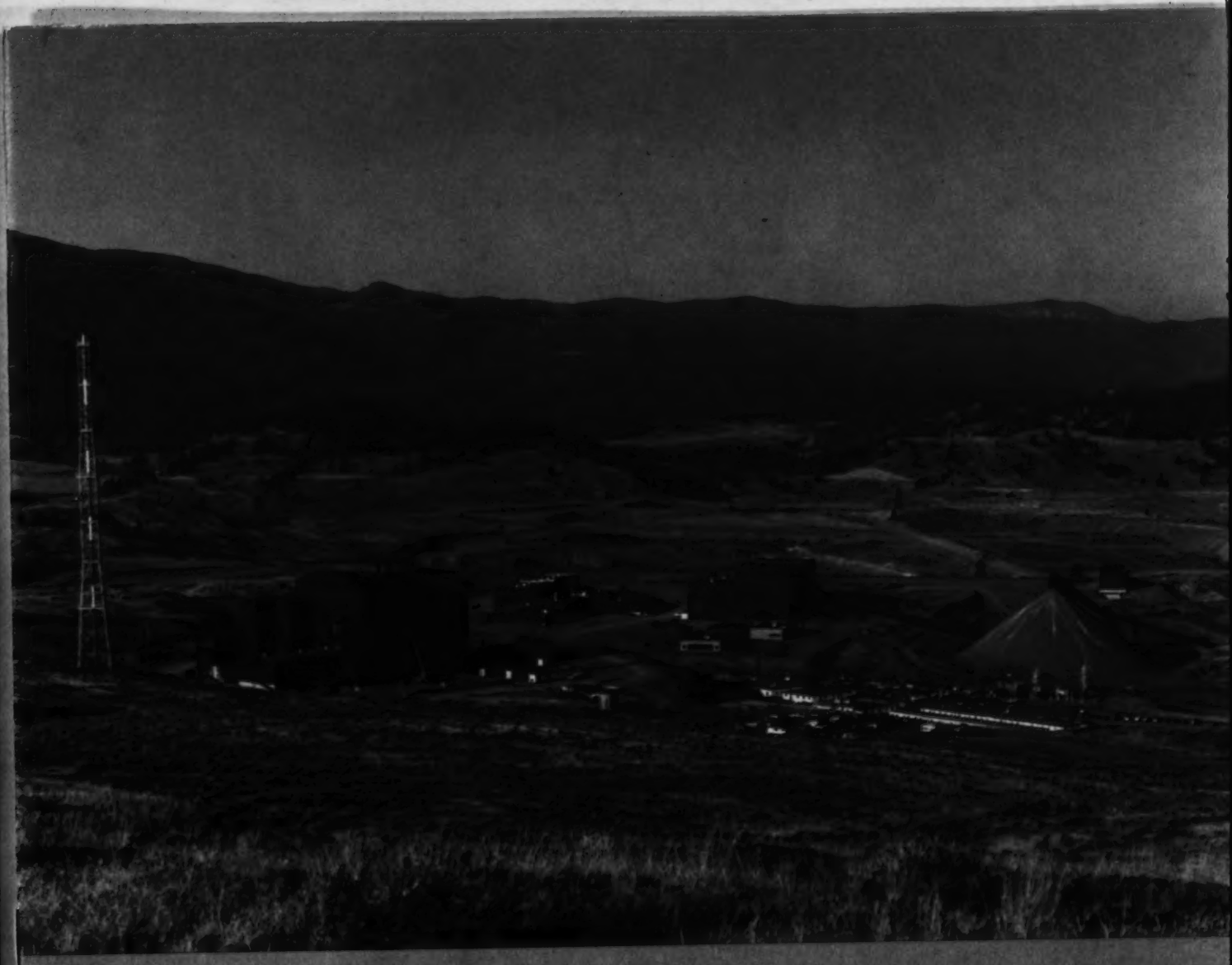
Breakseals containing sample SO_2 gas are connected to the mass spectrometer inlet system. The breakseals are broken and SO_2 gas and line standard are introduced alternately with simultaneous collection of mass 64 ($S^{32}O^{16}_2$) and mass 66 ($S^{34}O^{16}_2$) done through ionization by a tungsten filament. The ratio mass 66 / mass 64 is measured by a voltmeter and a frequency converter and processed by a built-in computer. During each run the line standard mass 66 / mass 64 ratio was measured before and after each sample measurement. Four measurements of mass 66 / mass 64 were taken alternately on line standard and sample, and averaged

TABLE VII - 8

Calibration of Mass Spectrometer SO_2 Line Standard
Against Other Artificial SO_2 Standards

Standards	Average δS^{34}‰ (Versus Line Standard)	Calculated δS^{34}‰ (Versus Cañon Diablo Troilite)
NBS #120 (Native Sulfur)	- 2.63 ± 0.08	+ 1.45
NBS #200 (Ivigtut)	- 3.29 ± 0.06	+ 0.68
Troilite (Mayerthorpe, Peace River Meteorite)	- 3.21	+ 0.79
Pbs (Commercial Grade)	- 8.88 ± 0.05	- 5.73
$BaSO_4$ "merck" (Commercial Grade)	- 1.46 ± 0.13	+ 2.81
Pine Creek NW (Sour Gas)	+16.40	+23.49
Ag_2S (McMaster Standard)	- 8.50	- 5.34

to give a total of nine averaged mass 66 / mass 64 (4 sample and 5 line standard) readings for each sample run. The computer printed out the averaged mass 66 / mass 64 ratio of the sample versus that of the line standard. Five duplicate samples were run to check the reproducibility of the analyses. All duplicate samples gave results within the analytical precision of the isotopic measurements ($\pm$ 0.18‰).



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Auditors

Coopers & Lybrand, Vancouver, B.C.

Annual General Meeting of Shareholders
Queen Anne Room at the Hotel Georgia
on March 10, 1978, at 11:00 a.m. (Pacif

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Annual General Meeting of Shareholders
Queen Anne Room at the Hotel Georgia, 801 West Hastings St., Vancouver, B.C. on March 10, 1978, at 11:00 a.m. (Pacific Standard Time).

Cover Photo by W.J. Hadgkiss.

3d2

One of Afton's 100 ton trucks dumping the first load of ore into the primary crusher in August, 1977.

The grinding circuit in Afton's 7,000 tons per day mill, with the primary, semi-autogenous mill at left and the secondary ball mill at the right.

John Ander
Robert Hall
during cons
dam at Afto

Afton's TR
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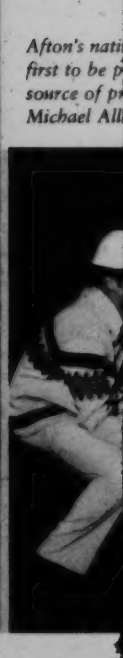
Michael All

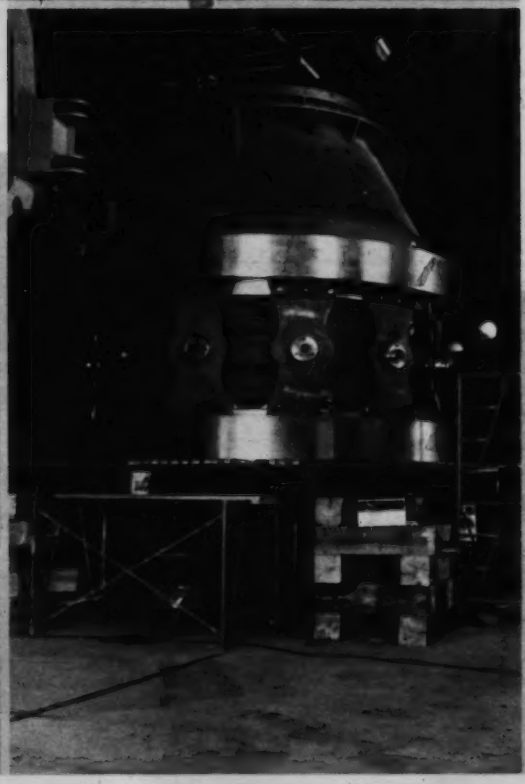


er, B.C.

100 ton trucks dumping the first load of ore into the r in August, 1977.

John Anderson, mine manager and Robert Hallbauer, managing director, during construction of the tailings dam at Afton.

ircuit in Afton's 7,000 tons per day mill, with the primary, s mill at left and the secondary ball mill at the right.



Afton's TRBC furnace as it arrived on the site, before being hoisted into place in the smelter.

Afton's native copper concentrate, the first to be produced in Canada, is a source of pride for Rod Hanson, Michael Allan and John Anderson.

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To the Shareholders:

1977 was an important year for Afton, with completion of the mine and mill and the first production of copper concentrate on December 9. Afton thus became western Canada's first new copper producer in five years, and the only significent new mine in Canada in 1977.

Two of the most important events for a new mining company are the discovery of an orebody and the start of production. Both usually represent the results of many years of work by a number of people, but there are always a few key individuals who deserve special recognition.

Afton was discovered by Chester Millar, who guided the exploration effort diligently from 1966 to 1972, when drilling indicated the presence of a commercial orebody. In the interval, the property was optioned to several major companies, each time being returned to Afton after further exploration proved discouraging. Chester Millar continued his persistent efforts, and in 1970 encountered mineralization in the eastern part of what is now the Afton orebody. By spring of 1972, drilling had progressed to the higher grade western side of the orebody, and it was clear that a mine was in the making. Chester Millar, and those that had backed him over the years, thus joined that small group of people who are Canada's mine-finders.

From 1973 onwards, management of the project has been the responsibility of Teck Corporation, under a contract to arrange financing and provide the expertise for efficient development and operation. Teck undertook the necessary feasibility and design engineering studies, not only of a mining and milling operation but of a smelter as well. These were completed and financing arranged by late 1975.

Construction began in June 1976 with this important phase being guided by Robert Hallbauer, Teck's vice president in charge of mining. Mr. Hallbauer and his design and construction staff have done a first class job on this, their third new Canadian mine to be completed in three years. They deserve the full appreciation of the company and its shareholders.

CONSTRUCTION

Open pit preparation by Afton crews and equipment began in April 1977, after initial work by a contractor. By the fiscal year end, 6,095,000 tons of material had been removed from the pit area and the mine was capable of supplying ore on a continuous basis to the mill. The tonnage moved included 3,932,000 tons of overburden, 1,722,000 tons of waste rock and 441,000 tons of ore.

Dr. Norman B. Keevil, Chairman of the Board, and Chester Millar on the Afton property shortly after d

Construction of the concentrator, sm
ings proceeded well, with the exception o
disputes. Eight weeks were lost in 1976
construction shutdown, and further costl
as a result of jurisdictional disputes betw
trator has now been completed and has be
ber 9. The smelter is in the final stages of co
to start up about the end of March. Cor
interval is being stockpiled.

By the end of the fiscal year a total
spent and $2,400,000 had been committe
Construction costs to completion, exclu
expected to be $85,000,000.

OPERATIONS

Operations during December were o
the performance of various parts of the
phase, ore grade was held to a level below
year. For this reason, and because mill
amount of mud and oxidized material f
coveries were not representative of the e
ance. The rated recovery and plant capaci
per day, respectively.

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Dr. Norman B. Keevil, Chairman of the Board, and Chester Millar on the Afton property shortly after discovery.

Construction of the concentrator, smelter and ancillary buildings proceeded well, with the exception of delays caused by labour disputes. Eight weeks were lost in 1976 due to a province-wide construction shutdown, and further costly delays occurred in 1977 as a result of jurisdictional disputes between unions. The concentrator has now been completed and has been operating since December 9. The smelter is in the final stages of construction and is expected to start up about the end of March. Concentrate produced in the interval is being stockpiled.

By the end of the fiscal year a total of $73,400,000 had been spent and $2,400,000 had been committed on equipment purchases. Construction costs to completion, excluding working capital, are expected to be $85,000,000.

OPERATIONS

Operations during December were of a tune-up nature, testing the performance of various parts of the concentrator. During this phase, ore grade was held to a level below that planned for the first year. For this reason, and because mill feed contained a certain amount of mud and oxidized material from the upper bench, recoveries were not representative of the expected ongoing performance. The rated recovery and plant capacity are 87% and 7,000 tons per day, respectively.

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COLOUR

A total of 134,856 tons of ore grading 0.76% copper was milled between December 9 and 31. This resulted in production of 988 tons of flotation concentrate grading 53% copper and 210 tons of gravity concentrate grading 75% copper, with recovery of 67%. Recovered gold and silver amounted to $1.96 per ton of ore milled.

Production in January averaged 7,400 tons per day for a total of 222,822 tons grading 0.90% copper. This resulted in 3,250 tons of flotation concentrate grading 40.5% copper and 451 tons of gravity concentrate grading 74.9% copper, and recovery had improved to 82.3%.

LABOUR RELATIONS

I am happy to say that relations have been excellent with our employees and their union, the United Steelworkers of America. We are operating on a two year contract which runs until April, 1979. Similarly, the labour performance by trades employed by the construction contractor was, for the most part, good. The one exception, aside from the province-wide construction shutdown early in the construction programme, involved a jurisdictional dispute between two unions.

The International Brotherhood of Electrical Workers, responsible to our contractor for electrical work on the property, chose to dispute the allocation of certain work to other unions. This resulted in a delay of at least one month in completion of the concentrator and two months in completion of the smelter. Although the work in dispute, involving installation of gauges and instrumentation, amounted directly to only some $50,000, the delays resulted in several million dollars of extra costs to Afton.

It is a serious problem for British Columbia when this kind of jurisdictional dispute can cause such costly delays. Jurisdictional disputes will come up, but if a mechanism cannot be found to resolve them more quickly, then future investors will have no alternative but to build provision for unnecessary overruns into their planning. If this means projects are cancelled or curtailed, it will add to costs, lower productivity, contribute further to inflation, and affect the well-being of all British Columbians including members of the labour unions.

The dispute was finally resolved after many months when the Minister of Labour appointed a special officer who upheld the original allocation of work and persuaded the union involved to get on with the job. What the Province needs is a mechanism to settle such disputes quickly, without resorting to costly illegal strikes or slowdowns. It would be constructive if union leaders would take the initiative in achieving such a mechanism.

REFINANCING

Arrangements are under negotiation to
the Afton project from $75 million to $8
convert the total to income debentures. Addi
$15 million U.S. continues to be available fr
ers. The effect of the conversion will be to lo
by approximately 4 percentage points. Th
million in the first year of operation is equ
pound of copper to be produced, and will
saving in these difficult times of weak copp

Details of this arrangement are in the
out. When this has been accomplished and n
been obtained, a special meeting of shareh
consider it.

It is with regret that we must report th
the year of E.P. Chapman and L.G. Whi
members of your Board of Directors. Th
spected mining engineers who had been de
ing industry in British Columbia for ma
valuable contribution to Afton during the p
they will be missed by us all.

I am pleased to report that J. Douglas
engineer with wide operating experience
board several years ago, has been re-ap
Directors.

I would like to express the apprecia
shareholders, to those employees of A
Wright Engineers, Dravo Corporation a
struction for their contribution to the pr

Vancouver, B.C.
January 27, 1978

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quickly, without resorting to costly illegal strikes or
would be constructive if union leaders would take the
hieving such a mechanism.

REFINANCING

Arrangements are under negotiation to increase bank loans for the Afton project from $75 million to $80 million U.S., and to convert the total to income debentures. Additional financing of up to $15 million U.S. continues to be available from our British customers. The effect of the conversion will be to lower Afton's interest cost by approximately 4 percentage points. The saving of some $3.2 million in the first year of operation is equivalent to about 6¢ per pound of copper to be produced, and will represent an important saving in these difficult times of weak copper prices.

Details of this arrangement are in the process of being worked out. When this has been accomplished and necessary tax rulings have been obtained, a special meeting of shareholders will be called to consider it.

It is with regret that we must report the untimely deaths during the year of E.P. Chapman and L.G. White, both of whom were members of your Board of Directors. These gentlemen were respected mining engineers who had been deeply involved in the mining industry in British Columbia for many years. They made a valuable contribution to Afton during the past two critical years, and they will be missed by us all.

I am pleased to report that J. Douglas Little, a consulting mining engineer with wide operating experience who served on the Afton board several years ago, has been re-appointed to the Board of Directors.

I would like to express the appreciation, on behalf of all the shareholders, to those employees of Afton, Teck Corporation, Wright Engineers, Dravo Corporation and Commonwealth Construction for their contribution to the project in the past year.

On behalf of the board

Vancouver, B.C.
January 27, 1978

N.B. Keevil Jr.
President

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CONSOLIDATED BALANCE SHEET AS AT S

ASSETS

	1977 $	1976 $
CURRENT ASSETS		
Cash and short-term deposits	3,036,767	2,210,520
Accounts receivable and prepaid expenses	163,991	3,547
	3,200,758	2,214,067
PROPERTY, PLANT AND EQUIPMENT		
Mineral properties, land and grazing leases, at cost	1,323,448	1,235,449
Construction in progress (note 2)	70,910,168	14,846,371
Deferred costs	3,357,917	3,357,917
Sugarloaf Ranch, at cost	698,165	525,710
	76,289,698	19,965,447
	79,490,456	22,179,514

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AUDITORS' REPORT TO THE SHAREHOLDERS

We have examined the consolidated balance sheet of Afton Mines Ltd. (N.P.L.) as at September 30, 1977 and the consolidated statement of changes in financial position for the year then ended. Our examination was made in accordance with generally accepted auditing standards, and accordingly included such tests and other procedures as we considered necessary in the circumstances.

In our opinion, these financial statements present fairly the financial position of the company as at September 30, 1977 and the results of its operations and the changes in its financial position for the year then ended in accordance with generally accepted accounting principles applied on a basis consistent with that of the preceding year.

Coopers & Lybrand

Vancouver, B.C.
November 10, 1977,
except for the
information presented in
note 9 for which the date
is December 23, 1977.

Chartered Accountants

AFTON MINES LTD. (N.P.L.)

TED BALANCE SHEET AS AT SEPTEMBER 30, 1977

	1976 $
767	2,210,520
991	3,547
758	2,214,067
448	1,235,449
168	14,846,371
917	3,357,917
165	525,710
698	19,965,447
456	22,179,514

LIABILITIES

	1977 $	1976 $
CURRENT LIABILITIES		
Accounts payable and accrued liabilities	1,656,307	1,329,830
Bank loan — current portion	6,433,800	
	8,090,107	1,329,830
LONG-TERM DEBT		
Bank term loan (note 3(a))	68,860,810	18,562,600
Teck Corporation Limited (note 3(b))	698,165	525,710
	69,558,975	19,088,310

SHAREHOLDERS' EQUITY

CAPITAL STOCK (note 4)		
Authorized —		
5,000,000 shares without par value		
Issued and fully paid —		
3,787,171 (1976 3,777,171)	1,920,427	1,840,427
DEFICIT	79,053	79,053
	1,841,374	1,761,374
	79,490,456	22,179,514

SIGNED ON BEHALF OF THE BOARD

Director

Director

ial position for
with generally
lied on a basis
ng year.

hybrand

ed Accountants

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CONSOLIDATED STATEMENT OF CHANGES IN FINAN

FOR THE YEAR ENDED SEPTEMBER 30, 1977

SOURCE OF WORKING CAPITAL
- Bank term loan .....
- Teck Corporation Limited (note 3(b)) .....
- Capital stock (note 4) .....

USE OF WORKING CAPITAL
- Construction in progress .....
- Mineral properties, land and grazing leases, Sugarloaf Ranch .....
- Deferred costs .....
- Mortgage .....
- Bank term loan currently maturing .....

INCREASE (DECREASE) IN WORKING CAPITAL .....

WORKING CAPITAL (DEFICIENCY) — BEGINNING OF YEAR .....

WORKING CAPITAL (DEFICIENCY) — END OF YEAR .....

REPRESENTED BY:
- Current assets .....
- Current liabilities .....

WORKING CAPITAL (DEFICIENCY) — END OF YEAR .....

CONSOLIDATED STATEMENT OF CHANGES IN FINANCIAL POSITION

FOR THE YEAR ENDED SEPTEMBER 30, 1977

	1977 $	1976 $
SOURCE OF WORKING CAPITAL		
Bank term loan	56,732,010	18,562,600
Teck Corporation Limited (note 3(b))	172,455	525,710
Capital stock (note 4)	80,000	
	56,984,465	19,088,310
USE OF WORKING CAPITAL		
Construction in progress	56,063,797	14,846,248
Mineral properties, land and grazing leases, Sugarloaf Ranch	260,454	823,181
Deferred costs		21,096
Mortgage		35,000
Bank term loan currently maturing	6,433,800	
	62,758,051	15,725,525
INCREASE (DECREASE) IN WORKING CAPITAL	(5,773,586)	3,362,785
WORKING CAPITAL (DEFICIENCY) — BEGINNING OF YEAR	884,237	(2,478,548)
WORKING CAPITAL (DEFICIENCY) — END OF YEAR	(4,889,349)	884,237
REPRESENTED BY:		
Current assets	3,200,758	2,214,067
Current liabilities	8,090,107	1,329,830
WORKING CAPITAL (DEFICIENCY) — END OF YEAR	(4,889,349)	884,237

NOTES TO CONSOLIDATED FINANCIAL STATEMENTS
FOR THE YEAR ENDED SEPTEMBER 30, 1977

1. SIGNIFICANT ACCOUNTING POLICIES

Principles of Consolidation

The consolidated financial statements include the financial statements of the company's wholly owned subsidiary Sugarloaf Ranches Limited.

Translation of Foreign Currencies

Amounts held in foreign currency are translated into Canadian funds at the following rates:

current assets and liabilities at year end rates;
other assets and liabilities at the rates prevailing at the date of acquisition.

Construction in Progress

Construction in progress represents accumulated project and financing costs.

Deferred Costs

Exploration, development and preproduction costs (including interest prior to commencement of construction) are deferred until the property to which they relate is placed in production. Deferred costs will be amortized over the useful life of the orebody following commencement of production.

2. CONSTRUCTION IN PROGRESS

Construction of mine, mill and smelter complex near Kamloops, having an estimated capital cost of $85,000,000, commenced in March 1976 with completion now scheduled for early 1978. Costs incurred to date, including deferred costs of $2,497,000, total $73,407,000, with firm commitments for an additional $2,443,000.

Teck Corporation Limited (Teck) and Iso Mines Limited (Iso), substantial shareholders of the company, have arranged financing for the project by way of a U.S. $75,000,000 term loan (note 3) and a U.S. $15,000,000 line of credit from the purchasers of the production. Teck and Iso have jointly and severally provided a completion guarantee for the project. In addition they have agreed to provide funds, up to a maximum of $25,000,000, for repayment of the bank loan in the event that the cash flow from the project is insufficient to meet scheduled repayments. There are provisions whereby the $25,000,000 commitment reduces as the bank loan is being repaid.

The U.S. $15,000,000 line of credit from the purchasers may be drawn upon if necessary to satisfy the completion and deficiency guarantees. To the extent that this line of credit is utilized, the obligations of Teck and Iso are reduced. The purchasers' loan, if any, will be secured by a second fixed and specific mortgage and floating charge on the assets and undertakings of the company.

The British Columbia Government has passed legislation which provides that it may enter into an agreement, subject to such terms and conditions as considered appropriate, to pay not more than five cents per kilo of blister or refined copper smelted or refined in British Columbia. The Government has indicated its intention to enter into an agreement with the company under this legislation, such agreement to be for a period of not more than 10 years with a maximum payment of $500,000 in any one year.

3. LONG-TERM DEBT

(a) Bank Term Loan

A U.S. $75,000,000 term loan has been arran
Canadian Banks. The loan is secured by a first
over all the assets of the company and by an assig
and the financing agreement with the concentr

Funds can be borrowed in either Canadian
repayment over eight years after commencemer
acceleration in the event of excess earnings as
ment. Minimum repayments of long-term deb
fiscal years ending September 30, are as follow

	$		
1978	6,000,000	1981	1
1979	13,000,000	1982	
1980	14,000,000		

Interest rates vary but at the present time th
Canadian funds and 130% of New York prim
U.S. $73,000,000 (Cdn. $75,294,610) has been
Agreement. This liability, U.S. $73,000,000,
proximately Cdn. $78,000,000 at September 3
November 11, 1977.

(b) Due to Teck Corporation Limited

The advances from Teck used to acquire and m
Limited are secured by the assets of Sugarlo
December 31, 1985 with interest at prime plu

4. CAPITAL STOCK

During the year the company issued 10,000 shares i
properties acquired at an ascribed amount of $80,00

5. DIVIDEND RESTRICTION

Under the terms of the bank loan, the company sh
dividends upon its share capital without the prior writ

6. ANTI-INFLATION ACT

The company is subject to the terms of the Anti-Infl

7. STATUTORY INFORMATION

No remuneration was paid to the directors or sen

8. CONTINGENT LIABILITY

An action for approximately $80,000 has been t
arising out of the relocation of the Trans Canada H
counsel for the company this action will be unsucces

9. SUBSEQUENT EVENT

On December 23, 1977, the company and Teck Co
commitment letters from their bankers covering prop
income debentures aggregating U.S. $80,000,000. If p
would replace the present indebtedness of the company
U.S. $5,000,000 of new financing in conjunction with
being developed and negotiated between the compa
Limited, details and terms of which are in the course

CONSOLIDATED FINANCIAL STATEMENTS
R ENDED SEPTEMBER 30, 1977

T ACCOUNTING POLICIES

Consolidation

ted financial statements include the financial statements of the olly owned subsidiary Sugarloaf Ranches Limited.

Foreign Currencies

in foreign currency are translated into Canadian funds at the s:

assets and liabilities at year end rates;

ets and liabilities at the rates prevailing at the date of acquisition.

n Progress

n progress represents accumulated project and financing costs.

s

evelopment and preproduction costs (including interest prior to t of construction) are deferred until the property to which they l in production. Deferred costs will be amortized over the useful body following commencement of production.

TION IN PROGRESS

of mine, mill and smelter complex near Kamloops, having an cost of $85,000,000, commenced in March 1976 with comple- d for early 1978. Costs incurred to date, including deferred costs otal $73,407,000, with firm commitments for an additional

tion Limited (Teck) and Iso Mines Limited (Iso), substantial e company, have arranged financing for the project by way of a term loan (note 3) and a U.S. $15,000,000 line of credit from the production. Teck and Iso have jointly and severally provided a ntee for the project. In addition they have agreed to provide ximum of $25,000,000, for repayment of the bank loan in the h flow from the project is insufficient to meet scheduled repay- provisions whereby the $25,000,000 commitment reduces as the g repaid.

000,000 line of credit from the purchasers may be drawn upon if fy the completion and deficiency guarantees. To the extent that is utilized, the obligations of Teck and Iso are reduced. The if any, will be secured by a second fixed and specific mortgage ge on the assets and undertakings of the company.

lumbia Government has passed legislation which provides that it agreement, subject to such terms and conditions as considered ay not more than five cents per kilo of blister or refined copper in British Columbia. The Government has indicated its intention reement with the company under this legislation, such agreement f not more than 10 years with a maximum payment of $500,000

3. LONG-TERM DEBT

(a) Bank Term Loan

A U.S. $75,000,000 term loan has been arranged with a consortium of Canadian Banks. The loan is secured by a first fixed and floating charge over all the assets of the company and by an assignment of the sales contract and the financing agreement with the concentrate purchasers.

Funds can be borrowed in either Canadian or U.S. currency with the repayment over eight years after commencement of production, subject to acceleration in the event of excess earnings as defined in the Loan Agreement. Minimum repayments of long-term debt for each of the next five fiscal years ending September 30, are as follows:

	$		$
1978	6,000,000	1981	11,000,000
1979	13,000,000	1982	8,500,000
1980	14,000,000		

Interest rates vary but at the present time they are prime plus 2% for Canadian funds and 130% of New York prime for U.S. funds. A total of U.S. $73,000,000 (Cdn. $75,294,610) has been borrowed under this Loan Agreement. This liability, U.S. $73,000,000, would be translated at approximately Cdn. $78,000,000 at September 30 and Cdn. $81,000,000 at November 11, 1977.

(b) Due to Teck Corporation Limited

The advances from Teck used to acquire and maintain Sugarloaf Ranches Limited are secured by the assets of Sugarloaf, and are repayable by December 31, 1985 with interest at prime plus ¾%.

4. CAPITAL STOCK

During the year the company issued 10,000 shares in consideration for mineral properties acquired at an ascribed amount of $80,000.

5. DIVIDEND RESTRICTION

Under the terms of the bank loan, the company shall not declare or pay any dividends upon its share capital without the prior written consent of the banks.

6. ANTI-INFLATION ACT

The company is subject to the terms of the Anti-Inflation Act and Regulations.

7. STATUTORY INFORMATION

No remuneration was paid to the directors or senior officers during 1977.

8. CONTINGENT LIABILITY

An action for approximately $80,000 has been taken against the company arising out of the relocation of the Trans Canada Highway; in the opinion of counsel for the company this action will be unsuccessful.

9. SUBSEQUENT EVENT

On December 23, 1977, the company and Teck Corporation Limited accepted commitment letters from their bankers covering proposed loans to be secured by income debentures aggregating U.S. $80,000,000. If proceeded with, these loans would replace the present indebtedness of the company to its bankers and provide U.S. $5,000,000 of new financing in conjunction with a proposed reorganization being developed and negotiated between the company and Teck Corporation Limited, details and terms of which are in the course of being settled.

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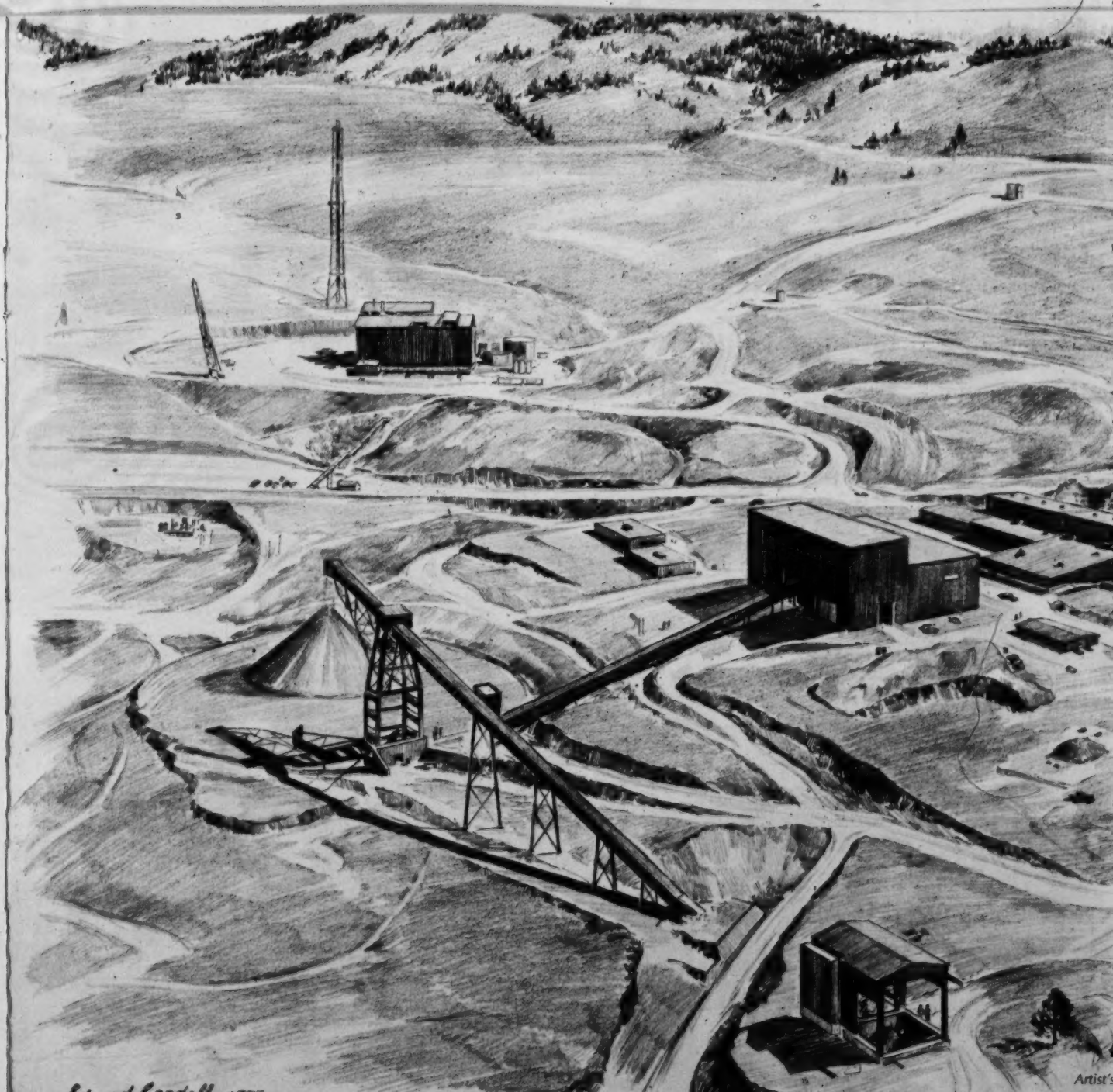
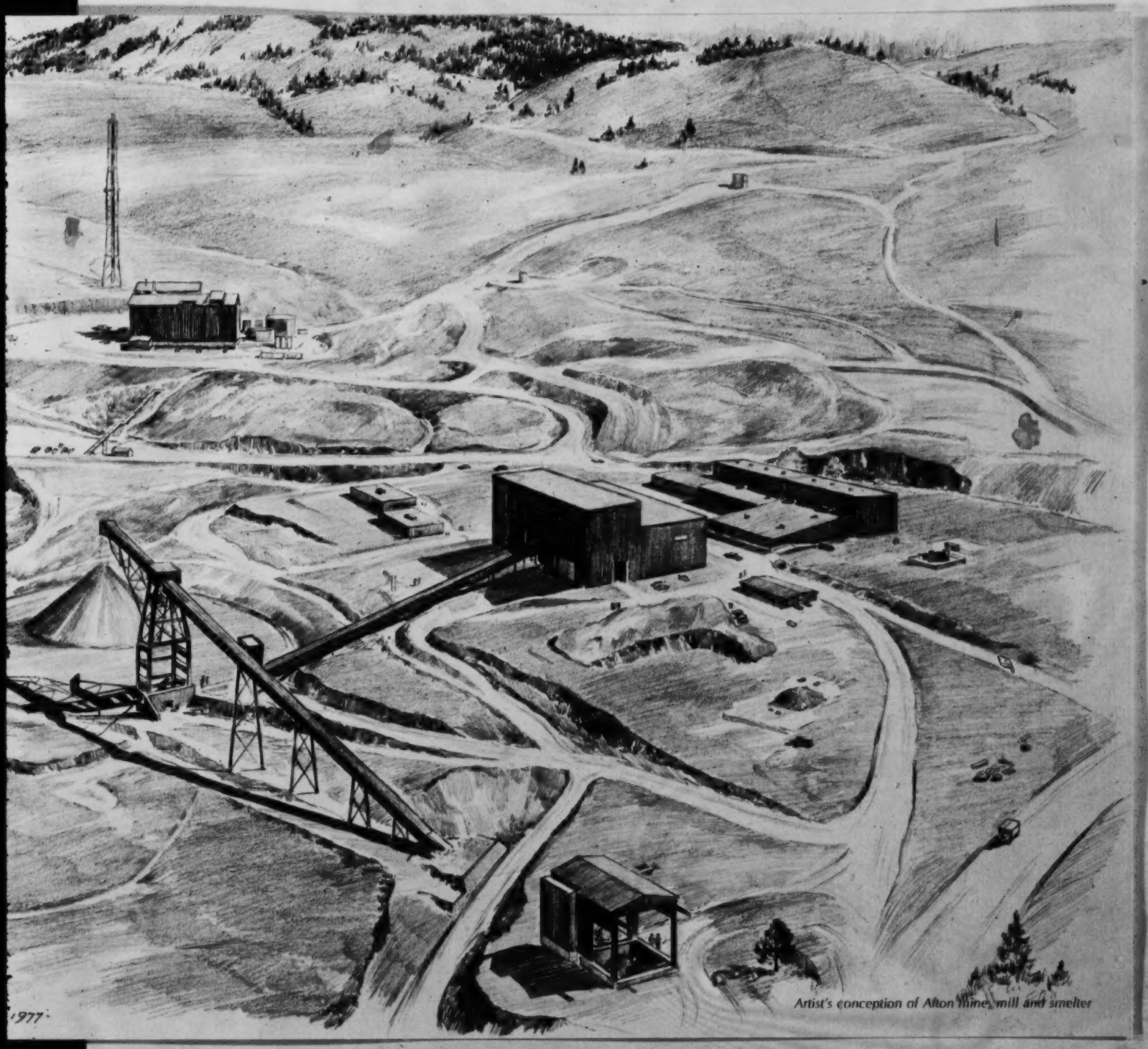

Edward Goodall 1977



Artist's conception of Afton mine, mill and smelter

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